



Massachusetts Military Reservation

PLUME RESPONSE PROGRAM

DRAFT SD-5 NORTH CONTAINMENT SYSTEM APPENDICES TO VOLUME 1

November 1996

*Prepared by:
Jacobs Engineering Group Inc.*

Document No.: AFC-J23-35K78403-M23-0001

SEE VOLUME 1 for ADDENDUM
which FINALIZES this REPORT

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APPENDIX A



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OPERATIONAL TECHNOLOGIES
C O R P O R A T I O N

July 10, 1996

Mr. Michael Minior
ANG/CEVRO
322 East Inner Road, Box 41
Otis ANG Base, MA 02542-5028

Subject: Fuel Spill 12 (FS-12) and Storm Drain 5 (SD-5) Plume Containment
System Groundwater Modeling Results

Dear Mr. Minior:

Attached per your request of July 9, 1996 is a copy of the subject documents. Please note that these were received from Environmental Consulting Engineers, Inc. in draft form and have not undergone rigorous internal review by OpTech.

If you have any questions regarding these documents, please do not hesitate to give me a call or Lorie Baker-Wallace can be reached at (423) 483-8020 for specific technical concerns.

Sincerely,

A handwritten signature in black ink, appearing to read "Kenneth G. Till". The signature is fluid and cursive, with the first name "Kenneth" being more prominent.

Kenneth G. Till
Deputy Project Manager

cc: Mr. John Morris, OpTech HQ (w/o atchs)
Ms. Lorie Baker-Wallace, OpTech OR (w/o atchs)
ANG File

STORM DRAIN 5 (SD-5) PLUME CONTAINMENT SYSTEM GROUNDWATER MODELING RESULTS

Environmental Consulting Engineers

1.0 INTRODUCTION

This report constitutes the Storm Drain 5 (SD-5) Plume Containment System (PCS) groundwater modeling results. This is an appendix to a more comprehensive groundwater modeling report (ECE, in preparation), as input to the SD-5 PCS design. As such, exhaustive detail is not included for some aspects of the modeling. Sensitivities and uncertainties relative to the groundwater modeling results, as well as design considerations, are included to aid the PCS design team in determining the appropriate safety factors to be incorporated into the design. Additionally, recommendations are made for the necessary hydrogeologic testing and conceptual/numerical model refinement which must be included in construction activities.

Based on the recommendations of the Technical Review and Evaluation Team (TRET) and the Plume Containment Process Action Team (PCPAT), groundwater modeling efforts were focussed on the SD-5 and Fuel Spill 12 (FS-12) (separate report) plume containment systems. The SD-5 Plume Containment System groundwater modeling efforts documented in this report were conducted between April 9, 1996 to June 19, 1996. As part of the TRET and PCPAT recommendations, several objectives were identified. Model development attempted to satisfy the objectives.

Groundwater modeling was conducted in a manner to ensure that stakeholder input was integral to the development of the final plume containment design scenario. Many different plume containment scenarios were developed based on stakeholder input and groundwater modeling considerations. The performance of each trial system (scenario) was then assessed against the established objectives. During this iterative process, several additional objectives were identified.

Well locations of the plume containment system were considered established once objectives were met to stakeholder satisfaction. The groundwater modeling efforts then focussed on system

optimization and investigation of the sensitivities and uncertainties inherent in the groundwater modeling.

All modeling results included in this report are subject to change based on any new data that may require an update or modification of the assumed model parameters.

2.0 PURPOSE AND OBJECTIVES

Listed below are the final criteria used to evaluate the performance of plume containment systems, simulated with the SD-5 groundwater models, in order of importance.

- Maximize capture of the SD-5 Plume with emphasis on areas of high contamination.
- Minimize impact of the system on the flux of groundwater to Ashumet Pond and Johns Pond.
- Minimize disturbance of the Western Aquafarm (WA) and Petroleum Fuel Storage Area (PFSA) Plumes.
- Minimize drawdown and mounding due to extracted and injected water.
- Facilitate constructability and minimize impact to existing land use areas outside the MMR boundaries.
- Minimize recirculation of treated water from injection to extraction wells.
- Minimize pumping rates.

The primary modeling objective was to balance the above criteria to a degree acceptable by all stakeholders. It should be noted that some of these objectives are conflicting and that an acceptable balance was accomplished through the iterative process.

3.0 ASSUMPTIONS AND MODEL PARAMETERS

Assumptions are necessarily inherent in groundwater modeling. For the purpose of this report, the assumptions and model parameters are divided into two categories as they relate to either 1) groundwater flow or 2) contaminant transport. The assumptions used for the groundwater modeling have been discussed and acknowledged by both the PCPAT and TRET. The assumptions for each of these categories are delineated below.

3.1 GROUNDWATER FLOW

It has been assumed that a saturated steady-state groundwater model is capable of adequately approximating groundwater flow for the SD-5 PCS design support. The groundwater modeling code FRAC3DVS (Therrien, R. et al., 1994) has been implemented for the groundwater flow modeling. Other groundwater flow modeling assumptions are tied to either physical parameters or to the conceptual understanding of the flow mechanisms in the vicinity of SD-5. The most important physical parameters are the hydraulic conductivity field (K-field) and aquifer recharge, and to a lesser extent, porosity. There is an inherent balance between recharge and the aquifer K-field. In general, a higher K-field requires higher recharge to obtain calibration in a groundwater model. The primary groundwater flow modeling assumptions used for the SD-5 plume containment design support are delineated below.

Hydraulic Conductivity

There are two K-fields that have been used for the SD-5 plume containment modeling. One K-field was developed by ECE based on aquifer testing data, and the other K-field was developed by the United States Geological Survey (USGS) for their Western Cape Cod (WCC) groundwater model. These two K-fields are termed ECE Defined and USGS Defined. A detailed description of

the ECE Defined K-field is presented in the main report (ECE, in prep.) and has changed little since it was first reported in the MMR Plume Containment System 60% Design, Massachusetts Military Reservation Cape Cod, Massachusetts (Operational Technologies, 1996). The ECE Defined K-field is based on a dual asymptotic function of K varying with elevation that was formulated from aquifer pump test and slug test results. In the vicinity of the SD-5 plume, the ECE Defined K-field within the aquifer has values ranging from 483 ft/day near the surface to 19.5 ft/day near the bottom of the aquifer, with a bulk average of 131 ft/day. A vertical anisotropy ratio of 5 to 1 was used for the ECE Defined K-field.

The USGS Defined K-field is based on extensive analysis of hydrostratigraphic data. In the vicinity of the SD-5 plume, the USGS Defined K-field within the aquifer has values ranging from 350 ft/day near the surface to 10 ft/day near the bottom of the aquifer, with a bulk average of 143 ft/day. The vertical anisotropy ratio used for the USGS Defined K-field was that reported in the USGS WCC modeling report (Masterson et. al., 1996). It was initially assumed that uncertainty in the K-field could be addressed by using both of these K-fields for the PCS modeling. However, the ECE Defined and the USGS Defined K-fields are not significantly different numerically, and there are not any significant hydrostratigraphic boundaries in the vicinity of the SD-5 plume. Thus, only part of the SD-5 modeling actually used the USGS K-field. Rather, it was assumed that using scalar multiples of the ECE Defined K-field would better address uncertainties in the K-field by providing a larger range of variation. Thus, it was assumed that scalar multiples ranging from 70% to 130% of the ECE Defined K-field would sufficiently address uncertainties in the K-field in the vicinity of the SD-5 plume.

Recharge

Using the above K-fields, certain aquifer recharge values are required to obtain acceptable model calibration. Recharge values from 27 to 29 inches per year are required to produce a calibrated model for the ECE Defined K-field. This range is dependent on the methodology used for simulating the groundwater/surface water interaction (discussed below). As with the K-field, it was assumed that recharge values ranging from 70% to 130% of the calibrated value would adequately address sensitivity/uncertainty in recharge values for the plume containment design.

Porosity

A 35% porosity was used for all SD-5 plume containment modeling.

Groundwater/Surface Water Interaction

The conceptual flow mechanism which has the greatest impact on the plume containment design is related to the groundwater/surface water interaction at Ashumer and Johns ponds. The most appropriate method for simulating groundwater/surface water interaction is a coupled groundwater/surface water model. However, for the purposes of the SD-5 plume containment design, it was assumed that simulating the ponds in a groundwater model is sufficient.

There are two methods which have been implemented for specifying the surface water bodies in the groundwater model. One method consists of specifying the ponds as constant head boundary conditions within the groundwater model. The other method consists of specifying the ponds as regions of high-K. It was assumed that a reasonable strategy for investigating the sensitivity/uncertainty in the groundwater/surface water interaction was to conduct the SD-5 plume containment groundwater modeling using both the constant head and the high-K approach.

3.2 CONTAMINANT TRANSPORT

There are many assumptions associated with simulating the movement of contaminants. It has been assumed that the use of particle tracking is sufficient for the plume containment design and that the time and expense associated with formal contaminant transport modeling is not warranted. The assumptions inherent in the use of the particle tracking methodology for simulating the movement of contaminants are delineated below.

- Dilution/attenuation is not a critical factor of the containment design.
- There is not a continuous source of contaminants which introduces additional contaminants into the system during the course of the plume containment operations.

- Each particle is representative of a volume of contaminated water, and this volume moves through the system with the particle.
- Each particle is representative of a mass of chlorinated volatile organic compounds (VOC), and this mass moves through the system with the particle.
- The chlorinated VOC plume, as delineated in the MMR Plume Containment Data Gap Field Work Technical Memorandum (Operational Technologies Corporation, 1996), was the plume represented by particle seeds.
- The longitudinal, transverse, and vertical dispersivity terms are 3.0 ft, 3.0 ft, and 0.01 ft, respectively. Values ranging from 0.0,0.0,0.0 to 10.0,10.0,0.01 were initially tested and it was found from source area seeding and plume development modeling that these values enabled the plume shape and concentrations to develop properly.

4.0 GROUNDWATER MODELS

There are two separate groundwater flow models used for the SD-5 Plume Containment modeling. These models are termed the "Constant Head Model" and the "High-K Box Model". The two models differ in both their lateral extents and the method in which groundwater/surface water interaction is simulated. The lateral (plan view) extents of the two models are shown in Attachment A. Scenario modeling and a brief description of each of the two models are presented below.

4.1 CONSTANT HEAD MODEL

The Constant Head Model is similar in all aspects to the groundwater model presented for the MMR Plume Containment 60% Design Document except for discretization, which has been refined for the SD-5 efforts. The SD-5 Constant Head Model has lateral discretization of 10 ft on a side in the areas of the plume. This model used the constant head pond approach. Specifics for this model including the model grid, calibration, steady-state water table plots, etc. are presented in

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Attachment A. As an additional calibration check, the SD-5 plume was seeded near the source area and the particle locations were tracked through time. Graphical illustrations of these plots are included in Attachment A.

For a "closed" type system such as the SD-5 PCS where extraction and injection is simultaneous and adjacent to one another, there are several advantages to using the constant head approach. This approach is generally sufficient to examine plume capture and other phenomena local to extraction and injection. This approach also has shorter model run times, is more numerically stable, and allows for coarser discretization which enhances modeling efficiency. The primary effect of this approach is that flow of groundwater to the ponds has a significant vertical component. Disadvantages with this approach pertain to simulating surface water bodies with potentially infinite sources/sinks of water.

4.2 HIGH-K BOX MODEL

The High-K Box Model uses the high-K pond specification approach. The boundaries were located such that under pumping conditions, boundary effects would not impact the pumping scenarios. For this box model, the boundaries were specified as constant head conditions with the head values based on the 1993 USGS Water Level Contour Map. Attachment A contains specific details for the steady-state model (baseline no-pumping case) including the model grid, calibration information, steady-state water table plots, etc. As an additional calibration check, the SD-5 plume was seeded near the source area and the particle locations were tracked through time. Graphical illustrations of these model runs are included in Attachment A.

The advantages to using the high-K approach to pond specification is better simulation of the flow to and through surface water bodies. This approach assumes that surface water flow can be approximated by a high K porous media. This approach produces more lateral flow to and from the ponds relative to the constant head approach. Disadvantages associated with the high-K approach relate to model stability, longer run times, and finer discretization requirements.

5.0 WELL CONFIGURATION SCENARIOS

In developing the SD-5 plume containment design, eight unique well configuration scenarios were developed, modeled, and evaluated. The well configuration modeling used the Constant Head Model. Each well configuration scenario is defined as a particular set of extraction and injection well locations. A particular scenario may have been used for a single model run or multiple model runs. This iterative process had a high-level of PCPAT, TRET, and other stakeholder involvement. Stakeholders have expressed satisfaction that the final well configuration (Scenario 8) achieves an acceptable balance of the identified objectives.

The 3-dimensional particle seeding scheme used during well configuration scenario modeling was refined during the interactive process. Initially (Scenarios 1–3), particles were seeded based on finite-difference cells. For this case, a single particle was placed at the centroid of each finite-difference cell located inside the 5.0 ppb Chlorinated VOC plume boundary as defined in the Data Gap Field Work Technical Memorandum (Operational Technologies Corporation, 1996). The particle seeding scheme was modified for Scenarios 4–6 such that particles were spaced uniformly within the plume boundary, independent of the finite-difference cells. This seeding scheme results in each particle representing a volume of 25,000 ft³.

Attachment B contains the groundwater modeling information and results for each of the well configuration scenarios. A brief summary of the materials included in Attachment B follows.

- Scenario Maps: Six maps showing the schematic diagrams of Scenarios 1–6.
- Run Summaries: Summary results of the Scenarios 1–6 model runs.
- Graphics: For the first 4 scenarios, few graphics were generated and results were presented in tabular form. For Scenario 5 and 6, graphics generally included a well location map, water table plots, and drawdown/mounding plots (difference in the water table under pumping conditions from the steady-state condition). Note that the extent that post-processing and evaluation of results varied from scenario to scenario depending on the emphasis of stakeholder concerns. In addition, new graphical tools were developed concurrently with

scenario development and evaluation. Thus, the graphics contained in Attachment B are not consistent from scenario to scenario but are included for completeness.

6.0 REFINEMENT AND OPTIMIZATION OF CONTAINMENT SYSTEM

Once an acceptable well configuration was achieved, which met the objectives and approval of the stakeholders, well locations were considered final and system optimization was conducted. The objectives of system optimization were to further improve system performance by modifying individual pumping rates on a well by well basis. Both the Constant Head and the High-K Box Model were used during the containment system optimization. Initial optimization was conducted using the Constant Head Model. Following optimization using the Constant Head Model, the system was then optimized using the High-K Box Model. The purpose of using both models was to ascertain the impact of the two approaches on the predicted PCS performance.

The particle seeding scheme was further modified for the optimization modeling. Contaminant mass attributes were associated with each particle using 3-dimensional 5.0 ppb, 10 ppb, and 100 ppb chlorinated VOC isoconcentration contours derived from the plan view map and cross sections presented in the Data Gap Field Work Technical Memorandum (Operational Technologies Corporation, 1996). The resulting particle seed configuration resembled several lumpy-concentric-oblate spheroids (shells within shells). Two different strategies were employed to associate the contaminant mass with each particle. The first is termed "Lower Bound" and is the least conservative approach whereas the second, termed "Upper Bound", represents the most conservative approach. These particle weighting schemes are explained below.

Scheme	Isoconcentration Contours	Assigned Concentration (ppb)	Assigned Mass (μg)
Lower Bound	5.0 ppb to 10 ppb	5.0	1.24
	10 ppb to 100 ppb	10	2.47
	> 100 ppb	100	24.78
Upper Bound	5.0 ppb to 10 ppb	10	2.47
	10 ppb to 100 ppb	100	24.78
	> 100 ppb	1000	247.8

The final optimized system is presented based on the high-K box model which required slightly lower pumping rates than the constant head model. This as well as the other optimization modeling information is presented in Attachment C. Attachment C contains run summary sheets and graphics associated with the optimization modeling. These are presented on a run by run basis. Note that the extent that each of the runs were post-processed and the results evaluated varied from run to run (i.e., if unfavorable results were obtained, further post-processing and evaluation efforts were not expended). Thus, the run summaries and graphics are not consistent from one model run to another. Existing information has been included for completeness.

7.0 FINAL PUMPING SYSTEM COMPARED TO OBJECTIVES

The final modeled SD-5 PCS performance was compared to the evaluation criteria. Each of the evaluation criteria and the modeled performance is addressed below. Attachment D contains information on the final SD-5 PCS modeling. Specifically, Attachment D contains modeling run summary information, well locations, well screen intervals, and associated graphics. The modeling results as related to the modeling objectives are discussed below.

7.1 MAXIMIZE CAPTURE OF THE SD-5 PLUME WITH EMPHASIS ON AREAS OF HIGH CONTAMINATION

Variability in both volume and mass capture between the Constant Head Model and the High-K Box Model are shown below. Note that the High-K Box Model achieves better calibration than the Constant Head Model. The better calibration results in better plume tracking and capture.

Model	Volume Captured	Total Mass Capture		Chlorinated VOC Mass Capture By Concentration Zone		
		Lower Bound	Upper Bound	≥ 100 ppb	100 to 10 ppb	10 to 5 ppb
High-K Box Model	98.93%	98.60%	98.51%	98.28%	98.84%	99.07%
Constant Head Model	83.19%	83.76%	82.51%	79.31%	86.83%	90.29%

* Chlorinated VOC isoconcentration contours as presented in the Data Gap Field Work Technical Memorandum (Operational Technologies Corporation, 1996).

7.2 MINIMIZE IMPACT ON THE FLUX OF WATER THROUGH ASHUMET POND

Modeling has indicated no significant impact on either Pond. This is expected due to the closed nature of the SD-5 PCS and its distance from the ponds.

7.3 MINIMIZE DISTURBANCE OF THE WA AND PFSA PLUMES

Due to the proximity of the WA Plume in areal and vertical space, it was significantly impacted by all SD-5 PCS Scenarios. The final model runs indicate a 60 to 70% of the WA volume is captured by SD-5 Scenario 6. There has been no observed dispersal or spreading of the WA Plume from any of the modeling runs.

None of the well configuration scenarios or any of the optimization modeling have shown any substantial impact on the PFSA Plume. The only impact observed with any modeling run is to capture a small portion (< 4% by volume) of the PFSA Plume. There has been no significant modeled dispersal or spreading of the PFSA plume as a result of the SD-5 PCS.

7.4 FACILITATE CONSTRUCTABILITY AND MINIMIZE IMPACT TO EXISTING LAND USES

Efforts were made during the development of the various well configuration scenarios for acceptable constructability and land use impact. Efforts were made to locate extraction and injection wells near existing roadways and away from the residential areas near Ashumet and Johns Pond, as well as the MMR flight line area. Stakeholder input and acceptance was critical in obtaining the final well configuration scenario.

7.5 MINIMIZE RECIRCULATION OF TREATED WATER

Groundwater modeling has shown that for the optimized scenario, less than 2% of treated water that has been injected recirculates back to an extraction well. This is due in part to the physical setting but primarily due to the offset in extraction and injection well screen intervals. Furthermore, testing was conducted to determine the quantity of contaminated water pumped verses total water pumped for several different time periods. The figure titled "Makeup of Pumped Water vs. Time" shown in Attachment D illustrates this relationship.

7.6 MINIMIZE PUMPING RATES

The process of minimizing pumping rates has been conducted to some extent. However, to acceptably meet the other criteria, the reported pumping rates are required. To illustrate this, the Pumping Efficiency Curves shown in Attachment D show how the various evaluation criteria change with pumping rate. For instance in Attachment D, it can be readily seen how volume and mass capture change with a change in pumping rate. This type of analysis is the extent to which pumping rates minimization was attempted. Further optimization and minimization of pumping rates should be conducted during the implementation and construction of the system when more information becomes available.

8.0 SENSITIVITY ANALYSIS

When the SD-5 PCS pumping strategy was finalized, modeling analysis of the sensitivity of the system to a variety of conditions was conducted. Both the High-K Box Model and the Constant Head Model were used for this analysis. However, emphasis was placed on the High-K Box Model because of better calibration.

To conduct this analysis, simulations were performed in which the primary parameters K-field, recharge, and pumping rates were systematically varied. The nomenclature used for the modeling runs correspond to percentages of the calibrated model's values for K-field, recharge, and pumping rates. For instance a (70,130,100) model run would correspond to a condition of a 70% scalar multiple of the K-field, with 130% of the calibrated recharge, and pumping at 100% of the final optimized pumping rate.

Mass capture, volume capture, and percentage of treated water recirculating from injection wells to extraction wells was investigated during this analysis. The change in flux through Ashumet Pond and Johns Pond were also investigated, no significant impact from the SD-5 Scenario 6 system was found.

Attachment E presents the results of the sensitivity analysis modeling runs. Several tables are provided which summarize the modeling runs under the various conditions. This information is also presented in a series of graphics. Run summaries and graphics are presented on a run by run basis for each of the modeling runs conducted for the sensitivity analysis.

General comments regarding the sensitivity analysis are summarized below.

- Volume and mass capture are *strongly dependent* on pumping rate.
- Volume and mass capture are *strongly dependent* on variations in the K-field and recharge.

- Pond flux is *strongly independent* on pumping rate.
- The percentage of recirculated water is minimal and *strongly independent* of variations in pumping rate, K-field, or recharge.
- Similar changes in both the K-field and recharge *do not significantly impact* any of the evaluation criteria.

9.0 UNCERTAINTIES

Uncertainties in the groundwater modeling can be attributed to uncertainties related to both the aquifer and to the contaminant plume. Aquifer related uncertainties arise primarily from unknowns in the physical properties of the aquifer itself and to some extent to uncertainties in the understanding of the flow mechanisms within the aquifer. Contaminant plume related uncertainties are primarily due to the definition of the plume itself. Both of these areas of uncertainty are discussed below.

9.1 AQUIFER

The inherently sparse nature of aquifer data specific to the SD-5 site yields uncertainties in aquifer properties. Localized heterogeneities in hydrostratigraphy, the distribution of K, the vertical anisotropy of K, and porosity all can have potentially adverse impacts on the plume containment system. Low-K zones such as small, thin confining layers of fine silts or clay or localized pathways of very high-K aquifer material are examples of these localized heterogeneities. Unfortunately, the occurrence of these localized phenomena is difficult to detect let alone estimate their potential impact. The modeling parameters used in the groundwater modeling and further tested in the sensitivity analysis represent a reasonable and extensive approach to addressing these uncertainties. However, design efforts should consider these uncertainties and make engineering decisions such that their impact on the objectives of the PCS is minimal.

Another uncertainty relating to the groundwater flow system pertain to the groundwater/surface water interaction. The groundwater modeling conducted for the SD-5 PCS and presented above show that there is substantial flow of deeper groundwater upward toward Ashumet and Johns ponds. Both the Constant Head Model and the High-K Model behave in this manner. These results are in keeping with other modeling studies such as those with the USGS WCC Model and the ABB SERGOU Model. There is some uncertainty of whether this is an artifact of numerical modeling or an actual representation of flow within the aquifer. This has been the topic of much discussion and study. The current conceptual understanding, supported by field observations, is that the upward flow to the ponds is indeed an actual process which occurs in this area and that the modeling accurately simulates this process.

Another area of groundwater flow related concern is the long-term viability and impact of the injection of treated water. These concerns arise from both the physical and the geochemical perspectives. The physical viability of the aquifer and the injection wells to accept treated waters through time is an uncertainty that needs to be addressed. Similarly, potential problems associated with the changes in aquifer geochemistry due to the injection of treated water also needs to be addressed. Neither of these concerns have been addressed by the groundwater modeling efforts to date. The overall strategy and ultimate performance for the SD-5 PCS is highly dependent on the ability of the injection wells to function properly. Thus, the design of the SD-5 PCS should consider these concerns and attempt to minimize their potential impact.

9.2 PLUME

Uncertainties pertaining to the contaminant plume are related to both the definition of the plume and to transport mechanisms affecting the plume. Uncertainties related to the physical plume definition arise from the sparsity and distribution of data defining the plume. Additionally, the efforts documented in this report are based on the Chlorinated VOC plume as defined in the Data Gap Field Work Technical Memorandum (Operational Technologies Corporation, 1996). The plume definition is a result of both Data Gap and Remedial Investigation data. Data Gap efforts focussed more on the leading edge and downgradient lateral boundaries. The Remedial Investigation data was used to completed the upgradient and internal plume definition. This results in a North-South elongated

plume that is very narrow in the East-West direction. The location of the extraction/injection fences is highly dependent on the plume definition. Uncertainties in the plume definition will inherently have significant impact on the performance of the SD-5 PCS.

There are also uncertainties attributed to the contaminant transport processes which may impact the movement of the plume under the stresses invoked by the SD-5 PCS. Among the processes which have not been addressed by these efforts are: primary and secondary contaminant sources, diffusion, degradation and related speciation, retardation (sorption, desorption), and other geochemical processes. The expected impact of these processes on the performance of the SD-5 PCS is unknown.

Although efforts have been made to minimize the drawdown and mounding from the extraction and injection well fences, any continual pumping of groundwater should consider subsidence as a possible consequence. Fortunately, anthropogenic structures near the SD-5 PCS are minimal, which helps mitigate this concern.

All of the above uncertainties and their potential impact to the performance of the SD-5 PCS should be considered in the design.

10.0 RECOMMENDATIONS

The scale and importance of the MMR plume containment efforts for the SD-5 PCS necessitate the implementation of a phased approach using adaptive management strategies for construction and operation. Although the SD-5 PCS is not of the scale as for the FS-12 PCS, there are still many variables of unknown certainty. The potential adverse affects upon human health and ecological habitats due to inefficient and/or incomplete performance of the PCS are unacceptable. Therefore, new information learned during SD-5 PCS implementation efforts should be used to modify the design (well and screen placement, etc.) as warranted. Groundwater modeling is an important aspect

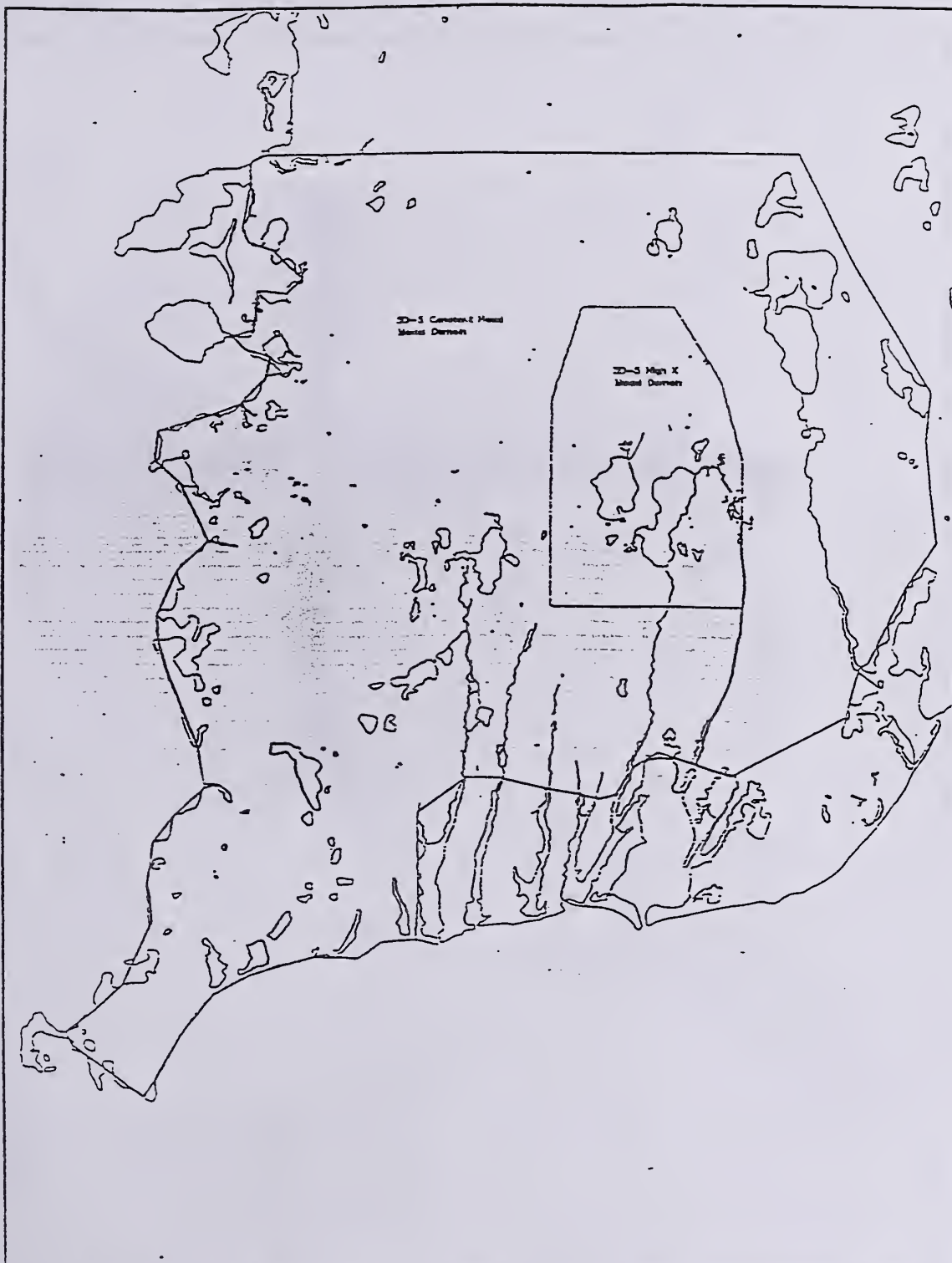
of this strategy and should be considered a recursive process integral to the construction, testing and operation of the SD-5 PCS.

Hydrostratigraphic and contaminant information collected during construction should be analyzed. Well drilling information such as geologic and geophysical data should be collected. Analytical information from both groundwater and aquifer matrix samples needs to be collected. Aquifer testing should include single and multiple well pumping tests, borehole flow meter testing, and injection testing should be performed for as many wells as possible during the initial phases and then as warranted for subsequent phases.

Any new information, such as localized heterogeneities which may have adverse affects to the performance of the SD-5 PCS, should be incorporated into the groundwater model(s) and their impacts rigorously assessed. The PCS should then be reoptimized and construction efforts modified based on the refined modeling results. Such design features that may be modified include screen intervals, well placement, and pumping rates.

It is also recommended that strong consideration is given to performance assessment and ecological monitoring. Chemical based performance monitoring may be inconclusive. Hydrologic monitoring, such as water level monitoring, may also be inconclusive due to masking from seasonal variations. Tracer based monitoring is the recommended methodology for evaluating the performance of the SD-5 PCS. Ecological monitoring, such as chemical and physical monitoring of Ashumet Pond, Johns Pond, and other ecologically sensitive areas should be conducted.

ATTACHMENT A



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Phone: (423) 551-0668
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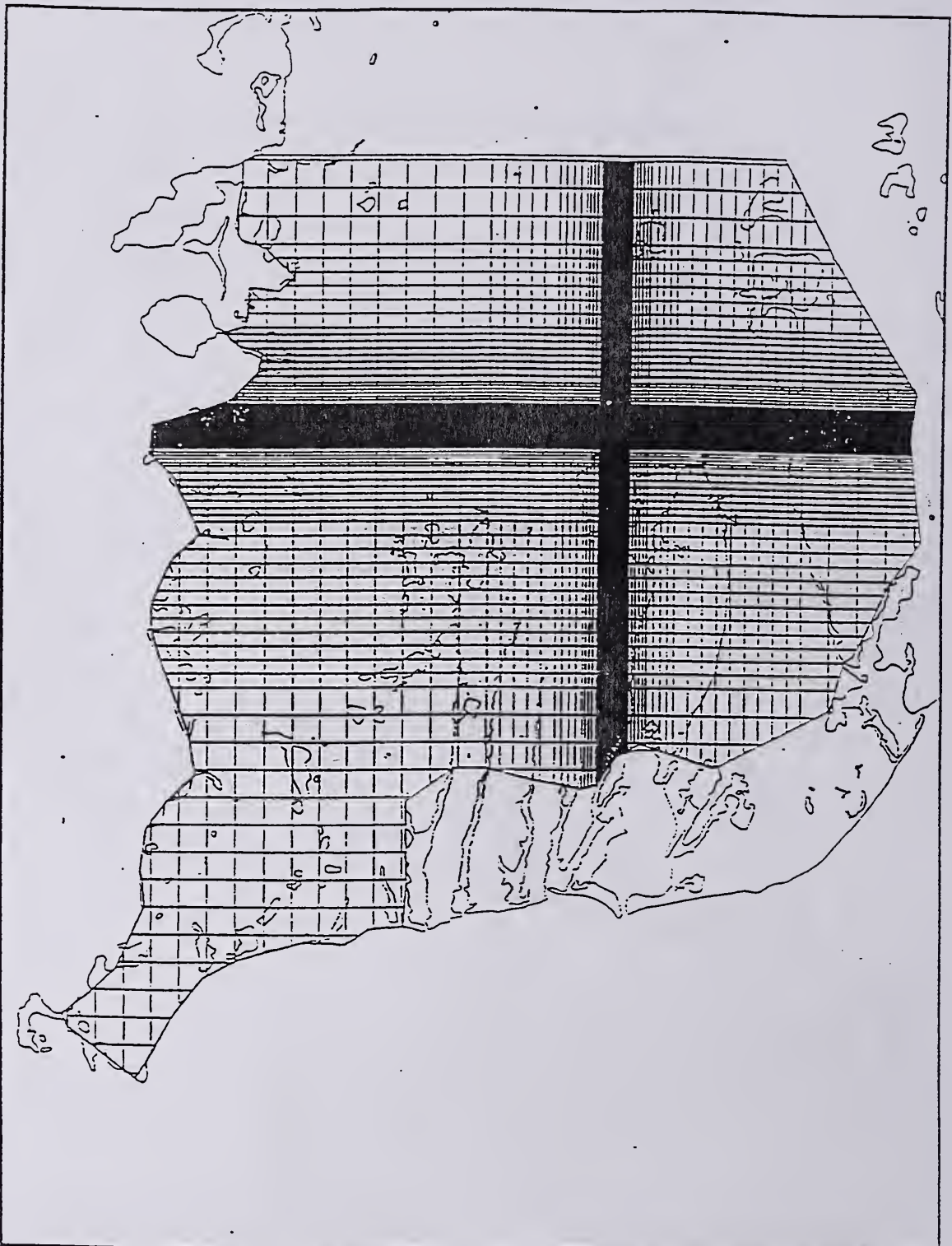
SD-S Constant Head and High K Model Domains

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: CHB
Checked by: VJC
Drawing Name: SD-S-SD-S.DWG
Project No.: CT MMR-01

Drawing No.

6.0619.04



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SD-5 Constant Head Model Grid

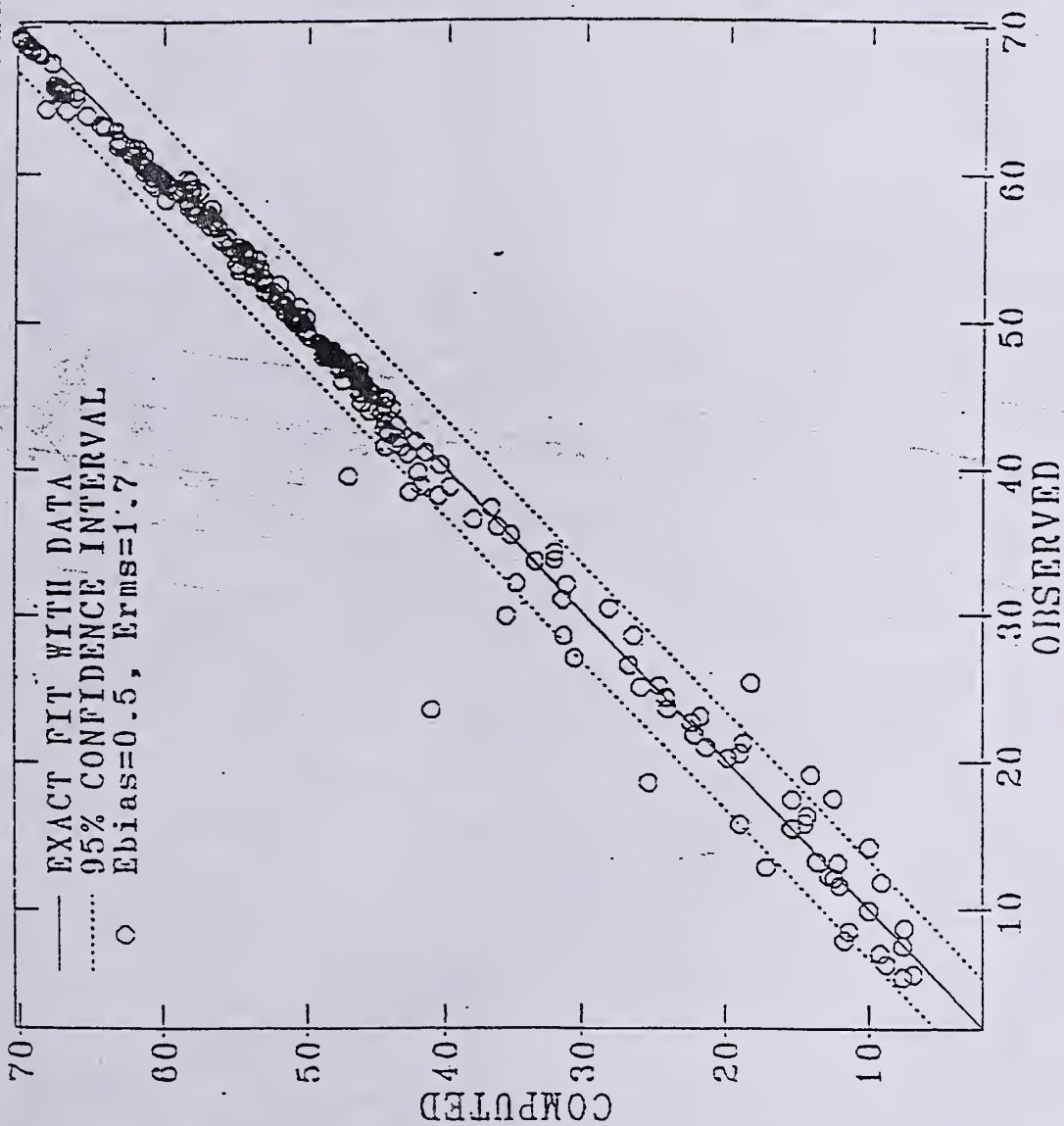
Massachusetts Military Reservation

Drawing Version No.: Rev. 3
 Drawn by: DHB
 Checked by: MLC
 Drawing Name: SD50-00.DWG
 Project No: 07 WMR.01

Drawing No.

6.0619.03

SD5 Constant Head Model: OBSERVED vs. COMPUTED HEAD





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SD-5 Constant Head Model Steady State Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 1
Drawn by: MLC
Checked by:
Drawing Name: SD5CHSS.dwg
Project No.: DT MMR-01

Drawing No.

6.0624.01



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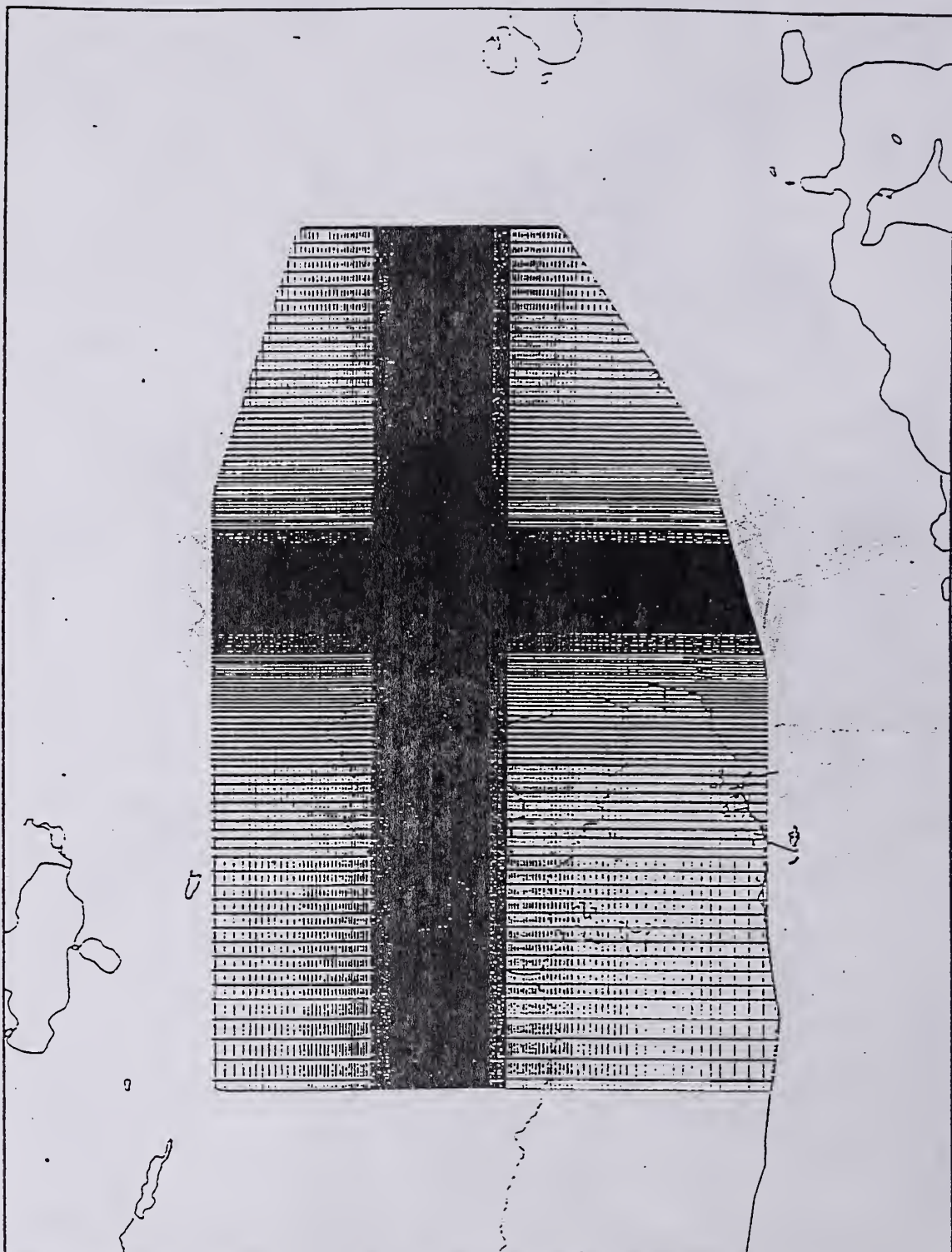
SD-5 Constant Head Model Source Seed
Locations 1, 2.5, 5, 10, 15, and 20 yrs

Massachusetts Military Reservation

Drawing Version No.: Rev. 2
Drawn by: MLC
Checked by:
Drawing Name: SD5CHRC10MC
Project No.: 07 VNR.01

Drawing No.

6.0624.01



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SD-3 High X Model Grid

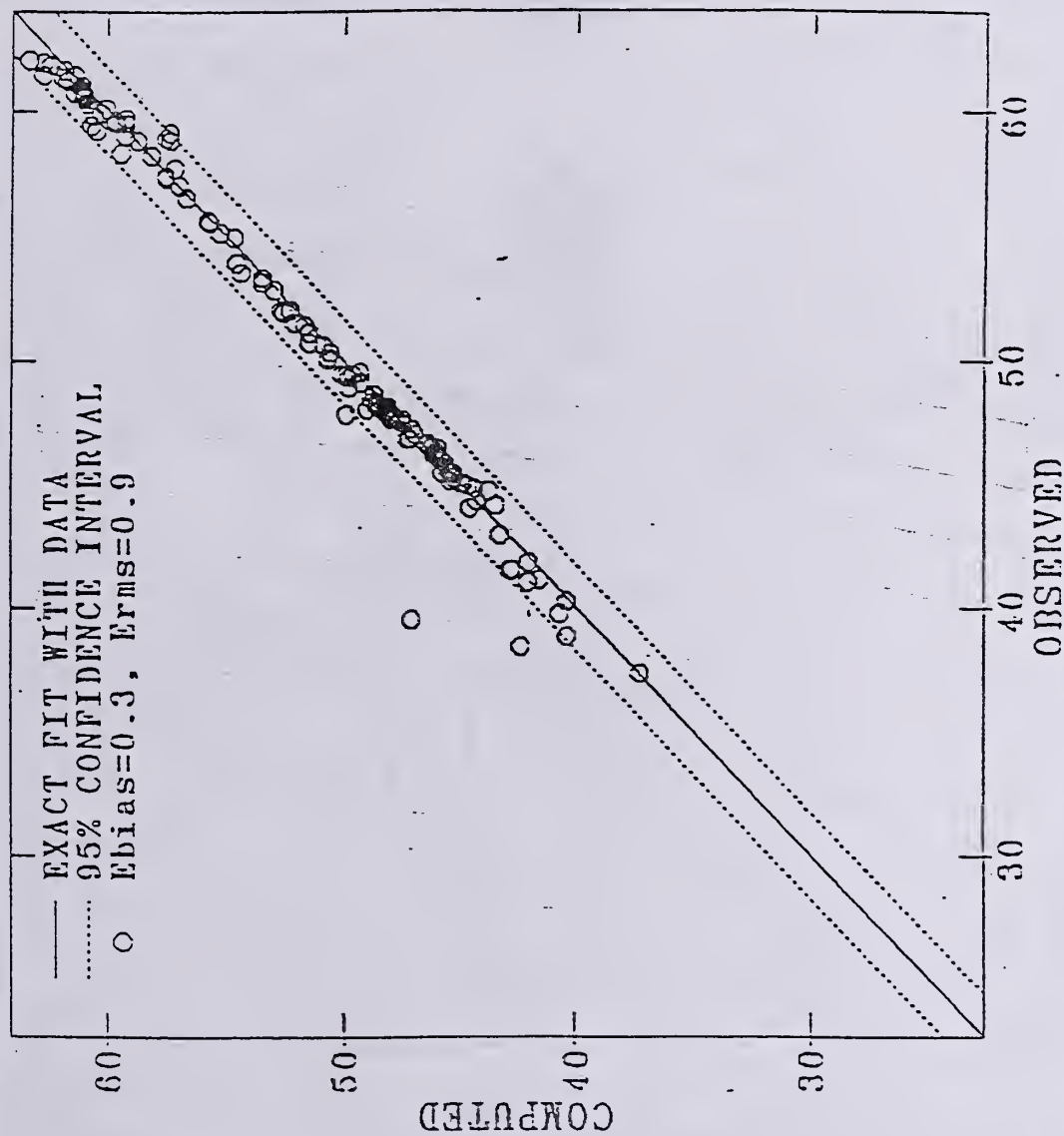
Massachusetts Military Reservation

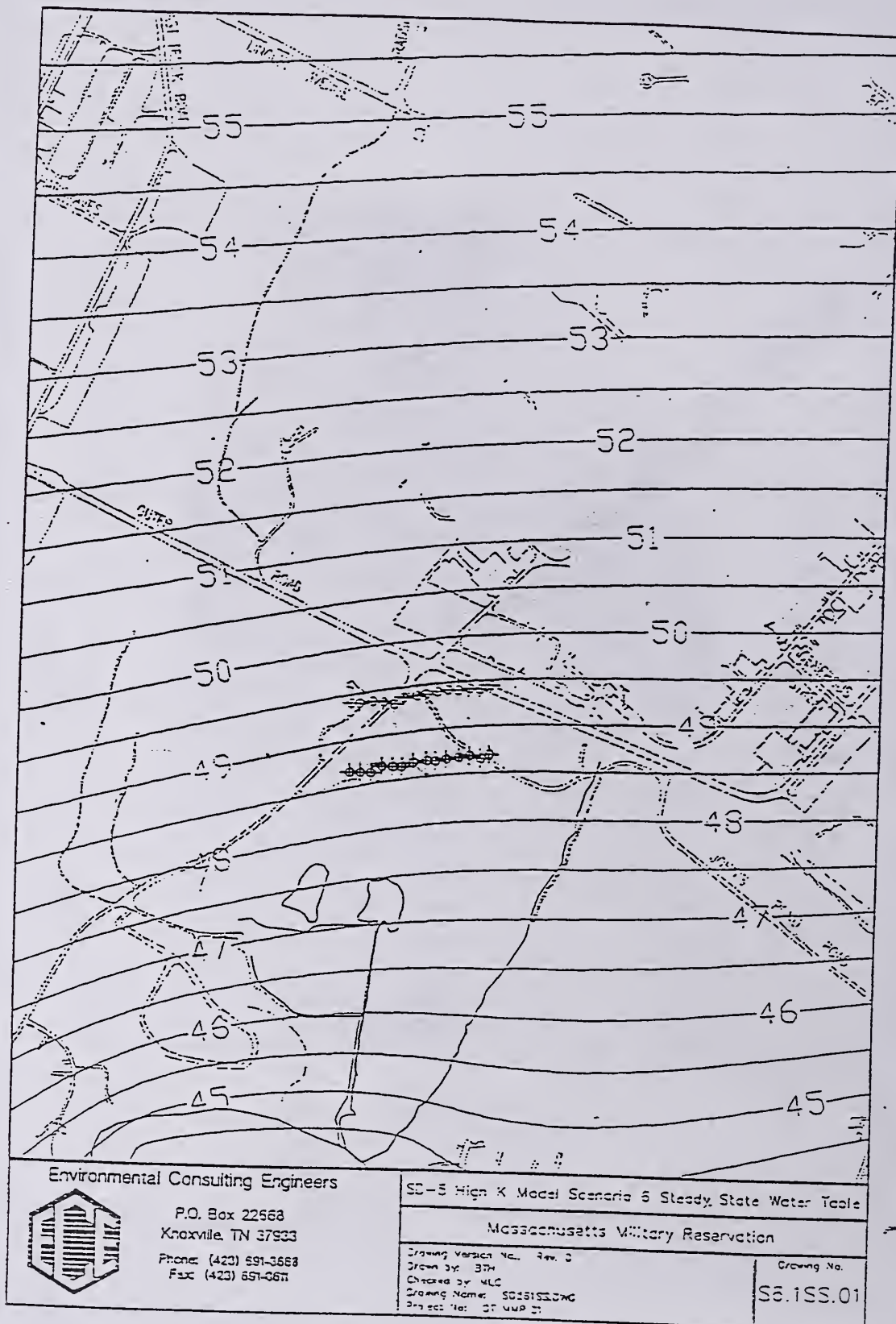
Drawing Version No.: Rev. J
Drawn by: DHE
Checked by: WLC
Drawing Name: SD3-HX-0100
Project No.: 01-00000

Drawing No.

6.0619.05

SD5HIK: COMPARISON OF OBSERVED AND COMPUTED HEAD







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SD-3 high K Model Source Seed
Locations 1, 2.5, 5, 15, and 20 yrs

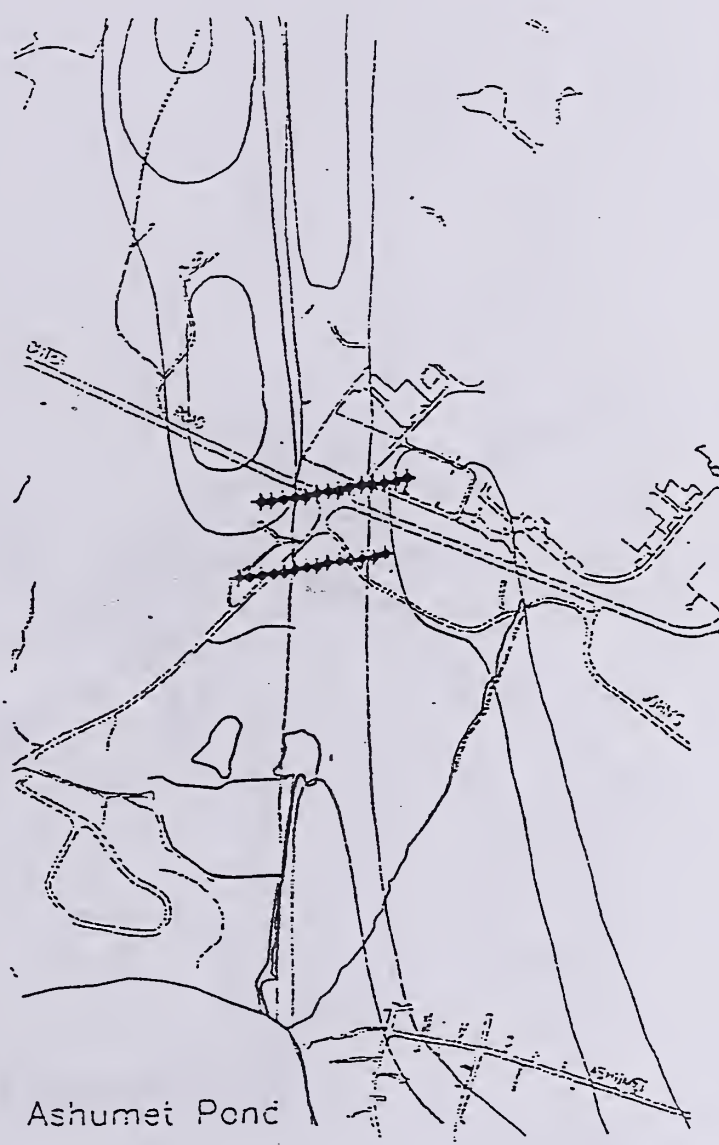
Massachusetts Military Reservation

Drawing Number: 6.0624.02
Drawn by: VLT
Checked by:
Drawing Name: SD-3 High K Model
Project No: 07-442-01

Drawing No.

6.0624.02

ATTACHMENT B



Ashumet Pond

SD-5 SCENARIO. 1

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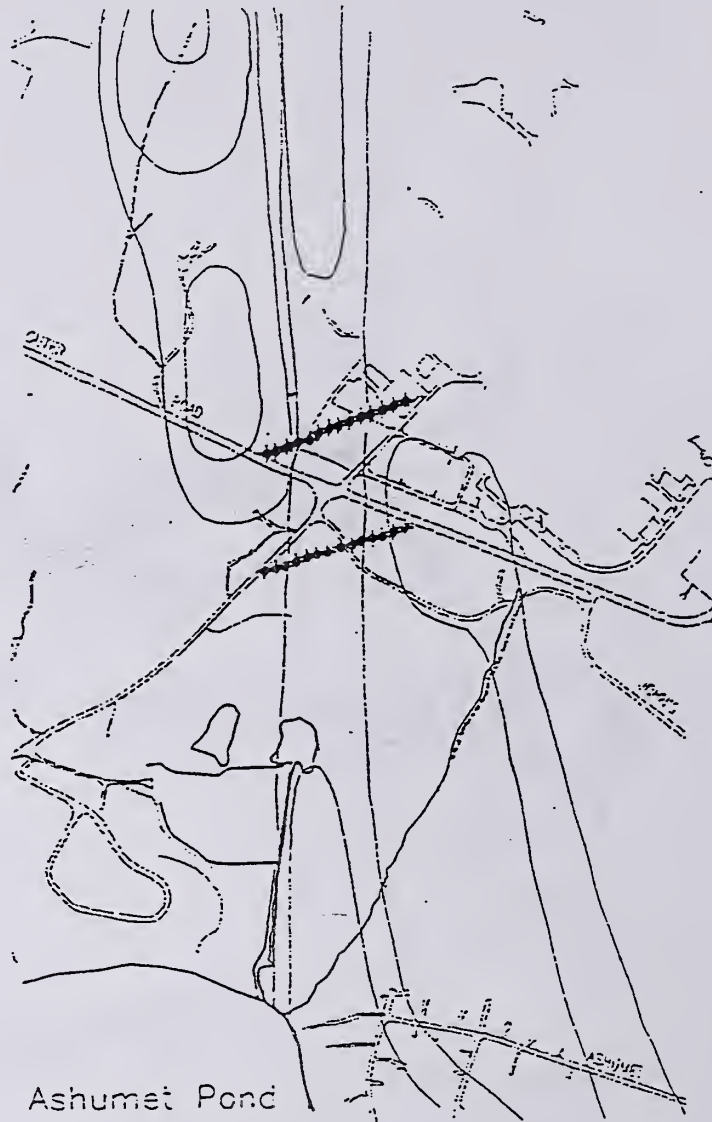
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Fax: (423) 591-0671

SD-5 PCS Scenario 1 Site Map

Massachusetts Military Reservation

Drawing Version No. Rev. 0
Drawn by: ULC
Checked by:
Drawing Name: SD510P9.DWG
Project No: 07 MAR 01

Drawing No.
6.0620.01



Ashumet Pond

SD-5 SCENARIO 2

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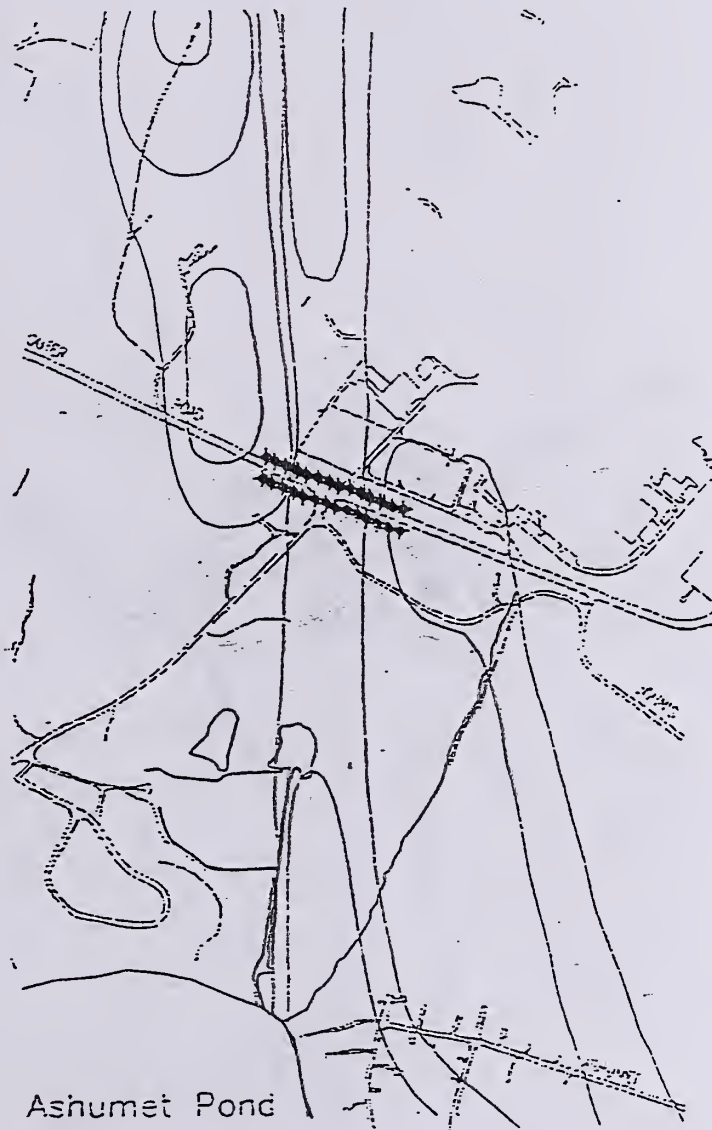
SD-5 PCS Scenario 2 Site Map

Massachusetts Military Reservation

Drawing version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD51199.DWG
Project No.: 07 WWP 01

Drawing No.

6.0620.02



Ashumet Pond

SD-5 SCENARIO 3

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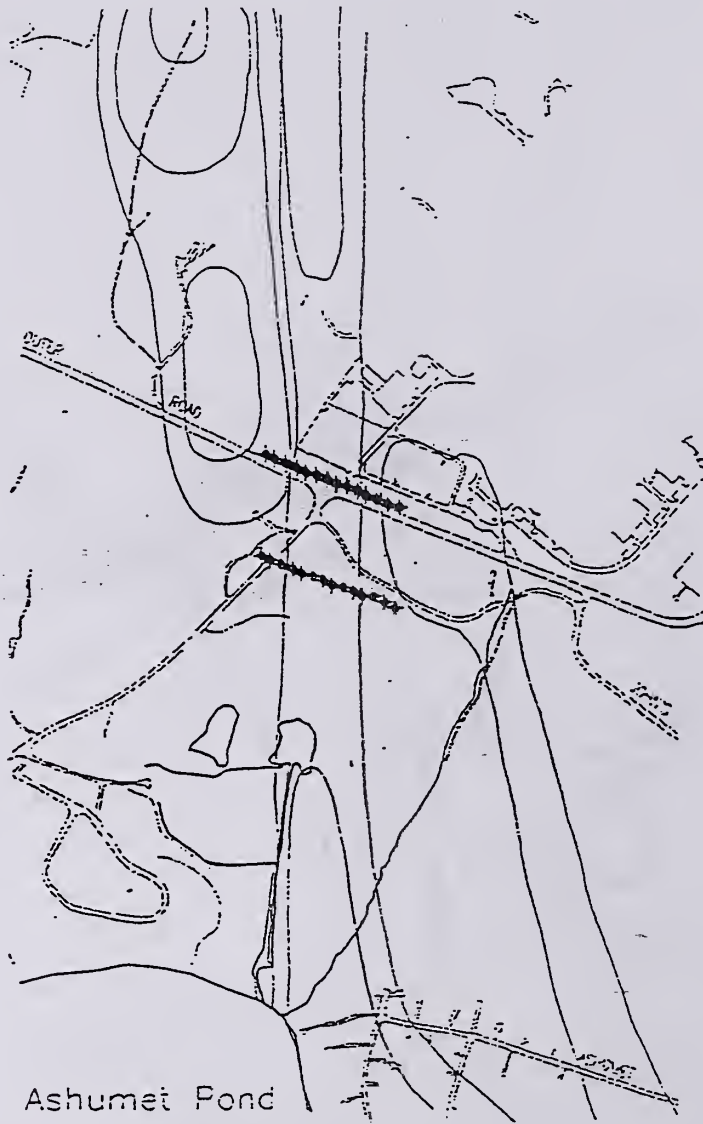
SD-5 PCS Scenario 3 Site Map

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: VLS
Checked by:
Drawing Name: SD5SITE.DWG
Project No.: 01-UMR-01

Drawing No.

6.0620.03



SD-5 SCENARIO 4

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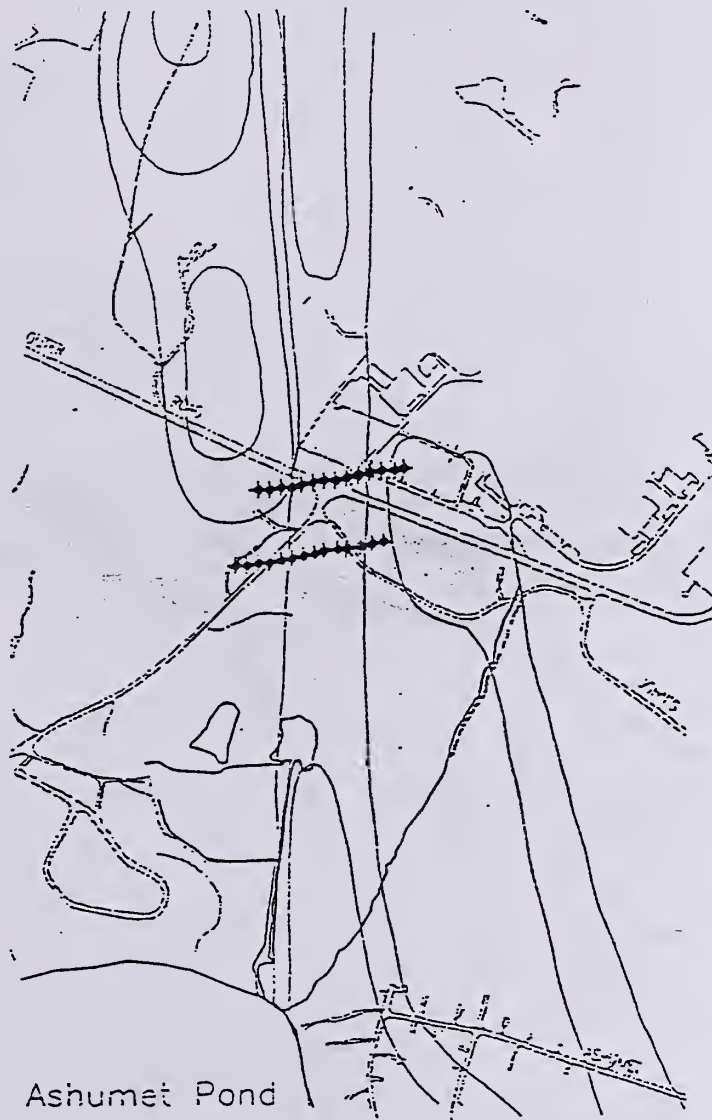
SD-5 PCS Scenario 4 Site Map

Massachusetts Military Reservation

Drawing Version: N.C. Rev. 0
Drawn by: M.C.
Checked by:
Drawing Name: SD5109.DWG
Project No: 07 VMD 01

Drawing No.

6.0620.04



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SD-5 SCENARIO 5

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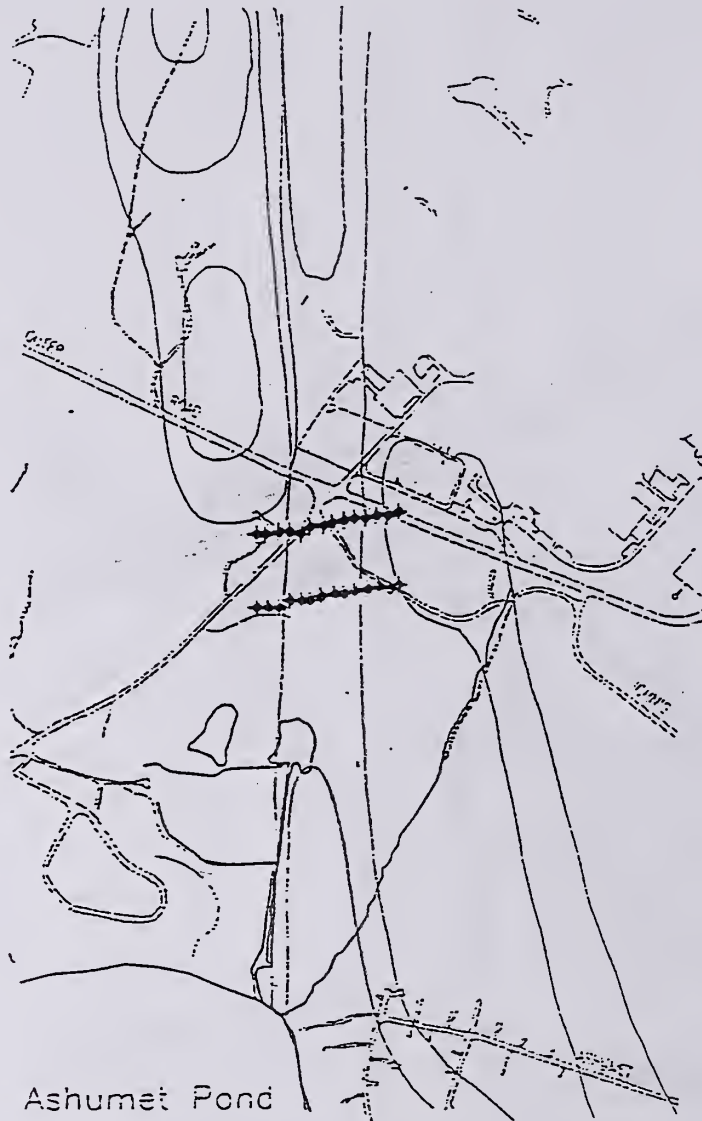
SD-5 PCS Scenario 5 Site Map

Massachusetts Military Reservation

Drawing Version No.: Rev 3
Drawn by: MLC
Checked by:
Drawing Name: SD25109.DWG
Project No: 01 442 01

Drawing No.

6.0620.05



Ashumet Pond

SD-5 SCENARIO 6

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SD-5 PCS Scenario 5 Site Map

Massachusetts Military Reservation

Drawing Version No. Rev. 3
Drawn by: MLC
Checked by:
Drawing Name: SD51379.DWG
Project No. 07 000 01

Drawing No.

6.0620.06

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MMR SD-5 PCS Scenario #1 Run 1
Model Run Summary
5-1-96

Model: Constant head

Recharge = 29 in/yr

Nodes = 415298

Elements = 378828

Wells = 28

- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Summary:

- The PCS Scenario #1 insufficiently captures the SD-5 Plume.
- The PCS Scenario #1 impacts the Western Aquifarm plume.
- The distance between extraction and injection wells produced unfavorable recirculation.

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MMR SD-5 PCS Scenario #2 Run 2
Model Run Summary
5-1-96

Model: Constant head

Recharge = 29 in/yr

Nodes = 415298

Elements = 378828

Wells = 28

- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Plume Particle Capture:

- Western Aquifarm: 247 of 789 (31.31%) particles captured.
- PFSA: 0 of 1118 (0%) particles captured.
- SD-5: 1861 of 4184 (44.48%) particles captured. Minimum northing (Y) value for extraction wells is 236570, thus all particles originating down gradient from this value are not captured. 2787 of the 4184 particles are upgradient (Y > 236570) of the extraction fence.

Conclusions:

- The PCS Scenario #2 insufficiently captures the SD-5 Plume.
- The PCS Scenario #2 impacts the Western Aquifarm plume.

Recommendations:

- Increase pumping rates for PCS Scenario #2 to complete capture of SD-5 plume upgradient of the extraction fence.
- Re-evaluate the proposed location for SD-5 PCS system to minimize the impact on the Western Aquifarm plume.

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MMR SD-5 PCS Scenario #3 Run3
Model Run Summary
5-1-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

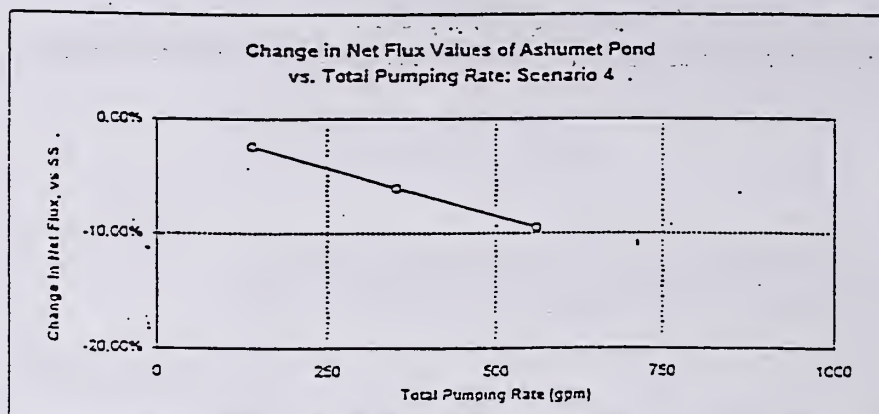
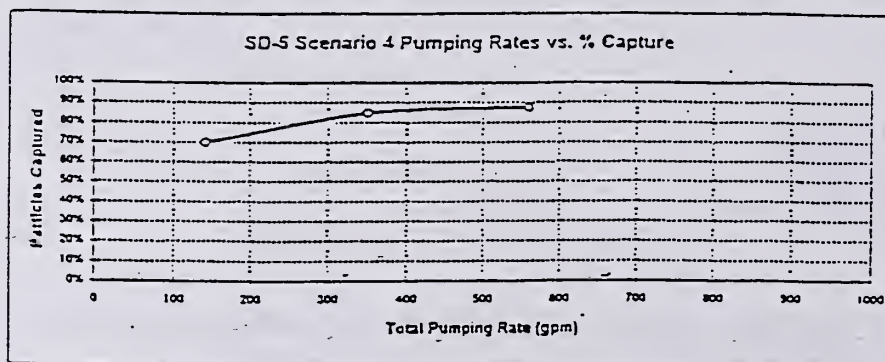
Wells = 28
- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Summary:

- The PCS Scenario #3 insufficiently captures the SD-5 Plume due to fence orientation with respect to equipotential lines.
- The PCS Scenario #3 impacts the Western Aquifarm plume.
- The distance between extraction and injection wells produced unfavorable recirculation.

SD-5 Plume Containment System Performance: Scenario #4												
SD-5 Total Pump Rate (gpm)	SD-5 Plume: SOSDB.SED			PFSA Plume: PFSA.SED			WAF Plume: WAF.SED			Ashumet Pond Fluxes (cfd)		
	total particles	particles captured	percent captured	total particles	particles captured	percent captured	total particles	particles captured	percent captured	In	Out	Net: Relative change vs. SS
-140	2948	2066	70.08%	1118	0	0.00%	789	187	23.70%	440751	-392545	-2.43%
-350	2948	2496	84.67%	1118	2	0.18%	789	370	46.89%	440602	-394200	-6.08%
-560	2948	2576	87.38%	1118	9	0.81%	789	511	64.77%	440467	-395766	-9.52%

RUN 4A
RUN 4B
RUN 4C



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MMR SD-5 PCS Scenario #4 Run 4A
Model Run Summary
5-14-96

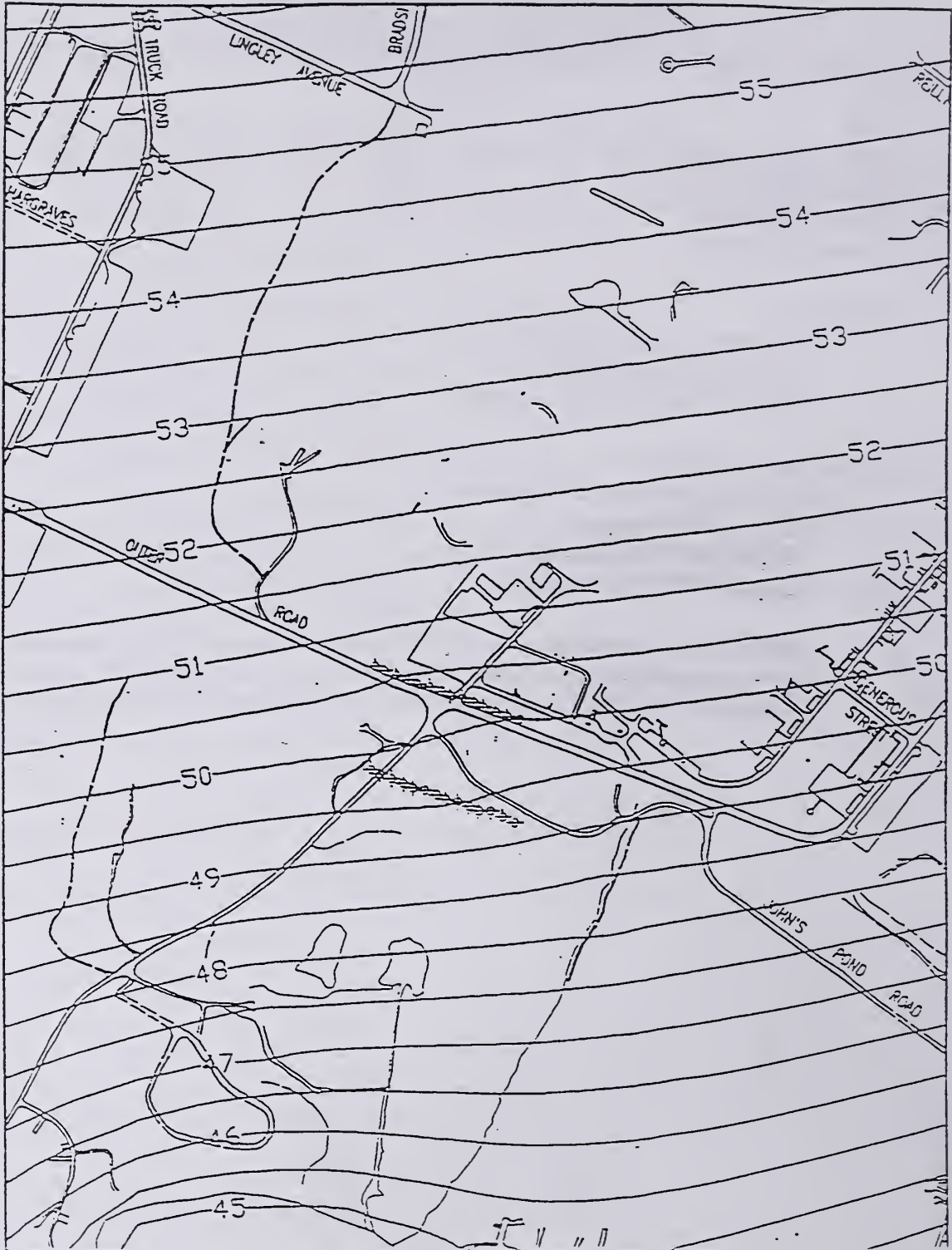
Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28
- 14 extraction wells (-10 gpm)
- 14 injection wells (10 gpm)
- TOTAL PUMP RATE = 140 GPM

Plume Particle Capture:

- Western Aquifarm: 23.70% capture.
- PFSA: 0.00% capture.
- SD5NORTH: 70.08% capture.
- SD5SOUTH: 0.00% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient ($Y > 236570$) of the extraction fence.



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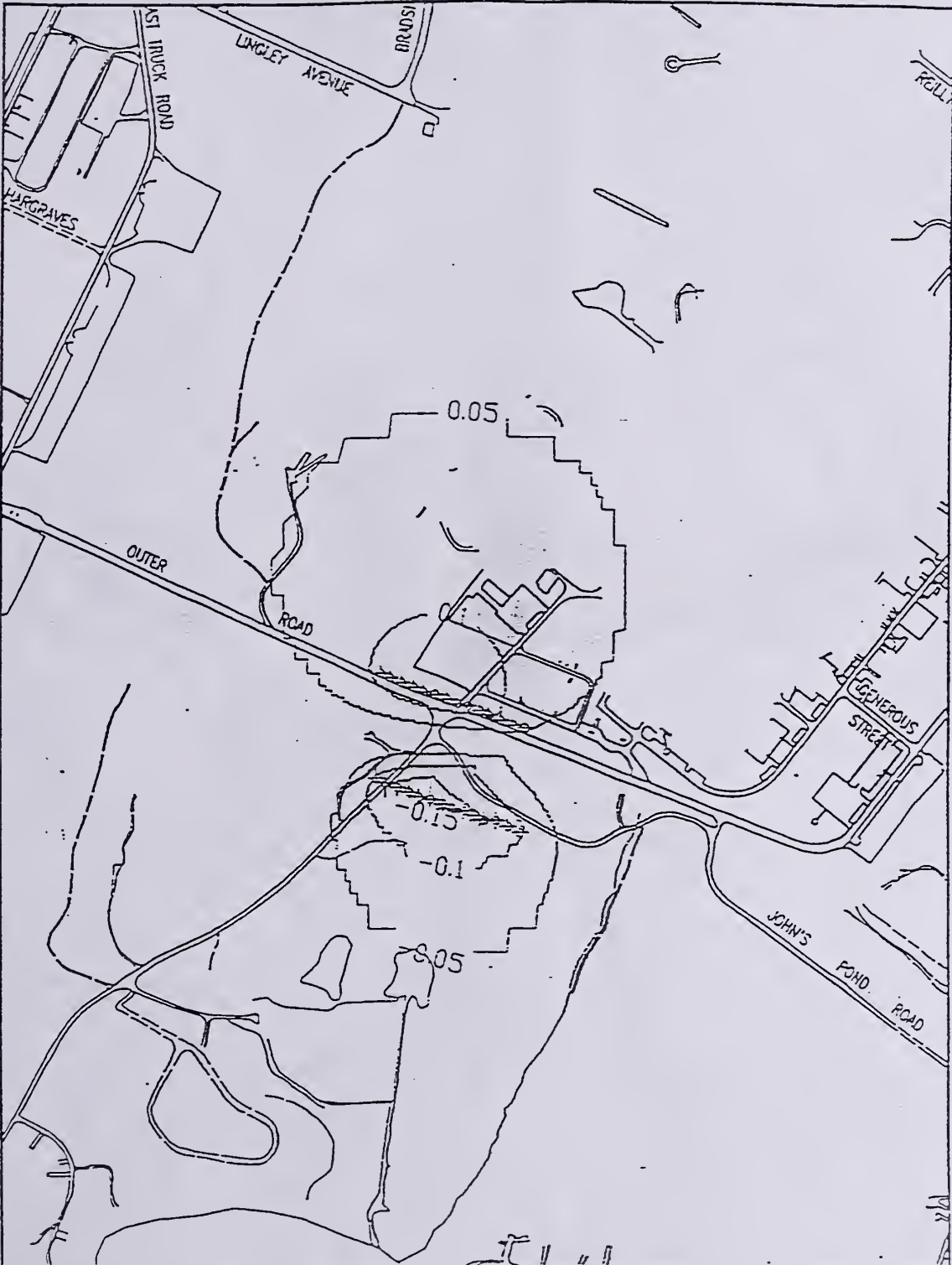
MMR SD-5 Scenario #4A (140 GPM) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: WLC
Checked by: LXS
Drawing Name: SD5_SMA3WG
Project No.: CT MMR01

Drawing No.

SD54c01



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MMR SD-5 Scenario #4A (140 GPM) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: MLC
 Checked by: LUC
 Drawing Name: SD5_DRAWING
 Project No.: 01 MAR-01

Drawing No.

SD54c02



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SD-5 Run 4A Particles Ending At Wells

Massachusetts Military Reservation

Drawing Version No. Rev. 3
Drawn by: ULC
Checked by:
Drawing Name: SD5_54A.DWG
Project No: OT UMR.21

Drawing No.

SD_4A



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SD-5 Run 4A Particles Ending At A Boundary

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: ULC
Checked by:
Drawing Name: SDS_SAADWC
Project No.: ST 4MR/21

Drawing No.

SD_4A

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MMR SD-5 PCS Scenario #4 Run 4B
Model Run Summary
5-14-96

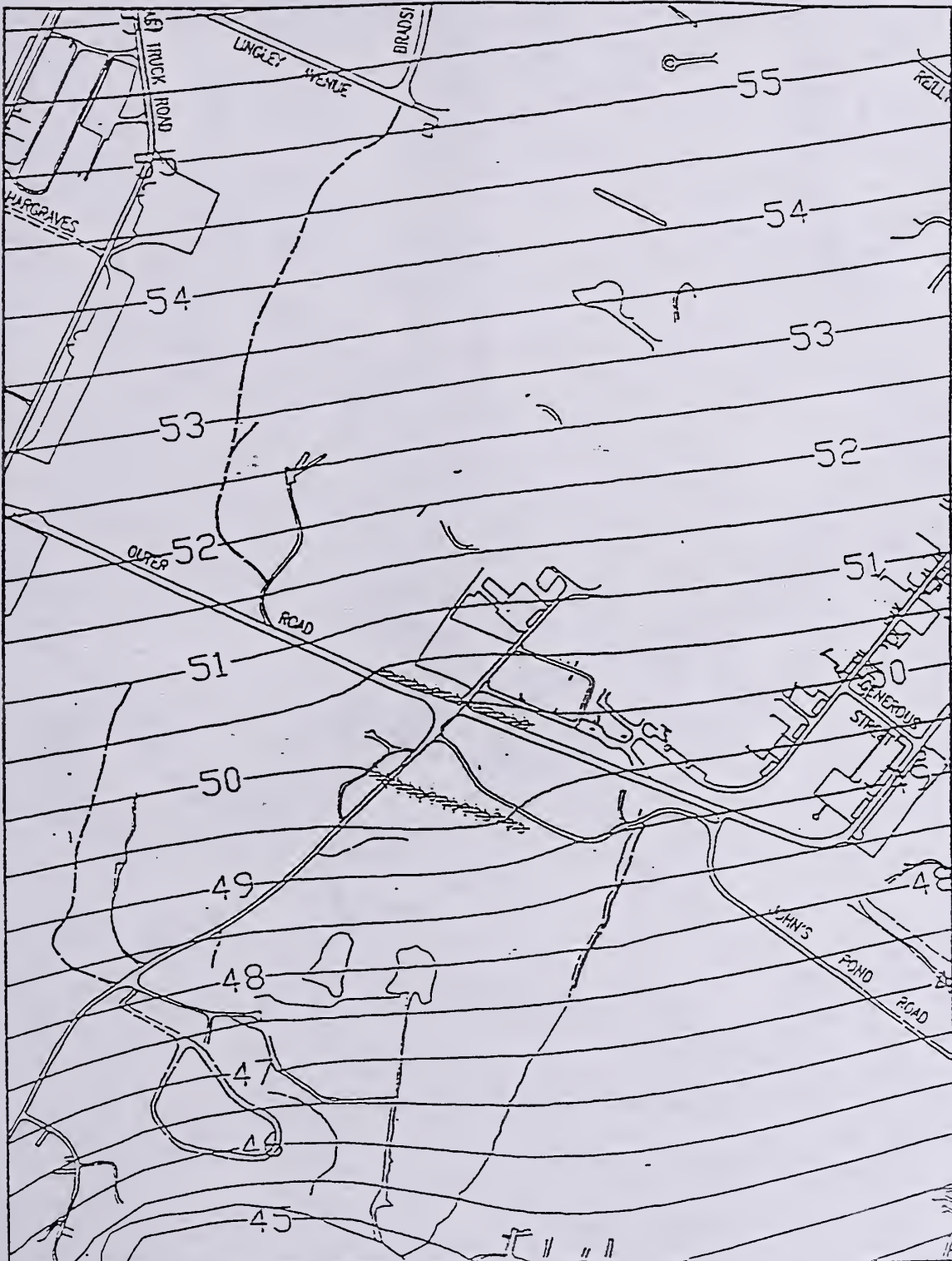
Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28
- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Plume Particle Capture:

- Western Aquifarm: 46.89% capture.
- PFSA: 0.18% capture.
- SD5NORTH: 84.67% capture.
- SD5SOUTH: 0.16% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.



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MMR SD-5 Scenario #48 (350 GPM) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: MLC
 Checked by: LYO
 Drawing Name: SD5_S48.DWG
 Project No.: CT VMR07

Drawing No.

SD54501



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MMR SD-5 Scenario #48 (350 GPM) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 3
 Drawn by: WLC
 Checked by: WLC
 Drawing Name: SDS_S48.DWG
 Project No.: 07 MMR-01

Drawing No.

SD545 02



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SO-5 Run 48 Particles Ending At Walls

Massachusetts Military Reservation

Drawing Version No.: Rev. 2
Drawn by: MLC
Checked by:
Drawing Name: SO5_S48.DWG
Project No.: 07 MMR 21

Drawing No.

SO_48



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SD-5 Run 48 Particles Ending At A Boundary

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: ULC
Checked by:
Drawing Name: SD5_548.DWG
Project No.: 21 UMR.21

Drawing No.

SD_48

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #4 Run 4C
Model Run Summary
5-14-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

- 14 extraction wells (-40 gpm)
- 14 injection wells (40 gpm)
- TOTAL PUMP RATE = 560 GPM

Plume Particle Capture:

- Western Aquifarm: 64.77% capture.
- PFSA: 0.81% capture.
- SD5NORTH: 87.38% capture.
- SD5SOUTH: 4.13% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.



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MMR SD-5 Scenario #4C (550 GPM) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by: LKD
Drawing Name: SD5_S4C.DWG
Project No.: CT WMR-CT

Drawing No.

SD54c 01



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MMR SD-5 Scenario #4C (560 GPM) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: MLC
 Checked by: LCB
 Drawing Name: SD5_S4C.DWG
 Project No.: CT MMR 01

Drawing No.

SD54c 02

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MMR SD-5 PCS Scenario #5 Run 5A
Model Run Summary
5-14-96

Model: Constant head

Recharge = 29 in/yr

Nodes = 415298

Elements = 378828

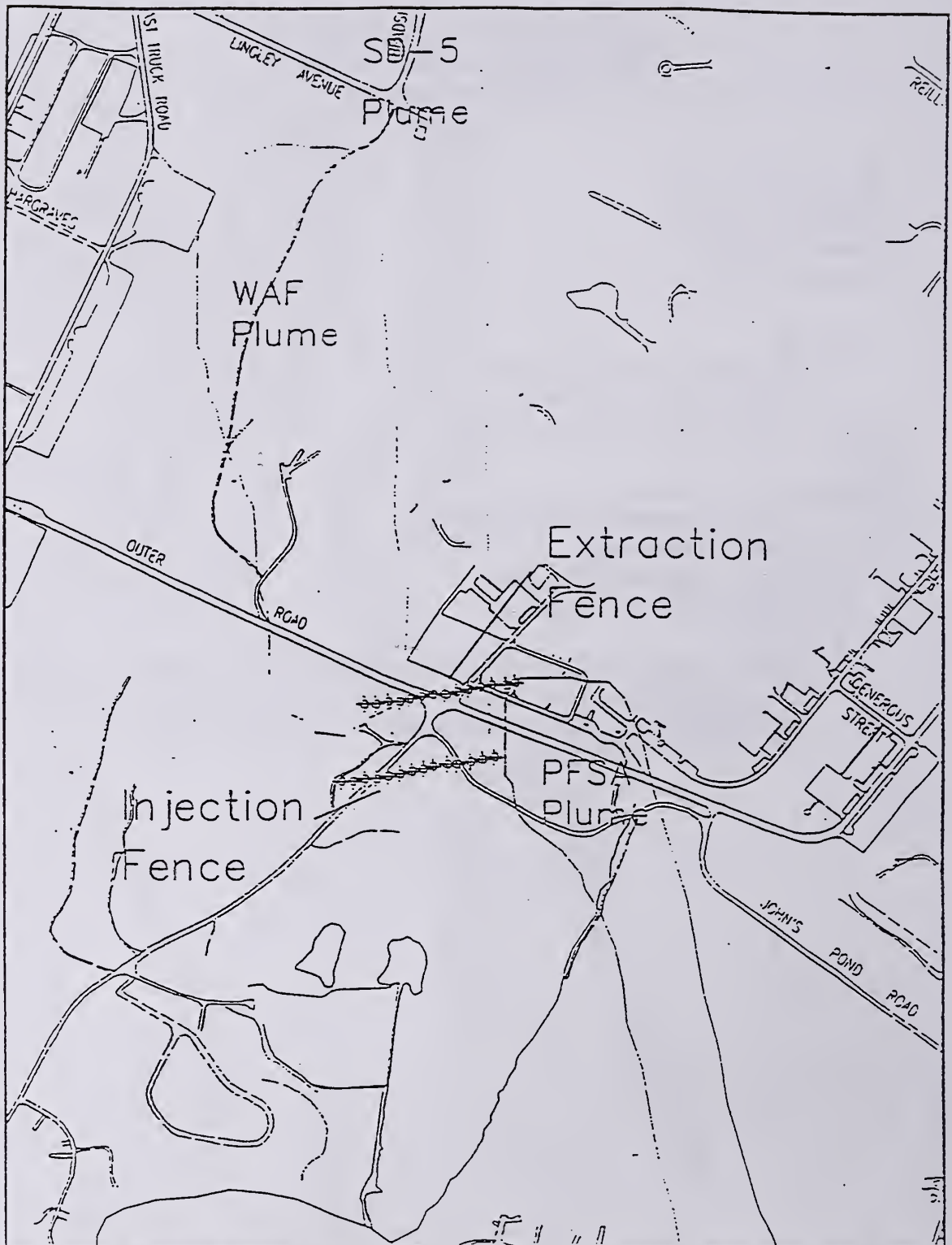
Wells = 28

- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Plume Particle Capture:

- Western Aquifarm: 56.02% capture.
- PFSA: 0.00% capture.
- SD5NORTH: 81.65% capture.
- SD5SOUTH: 0.65% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.



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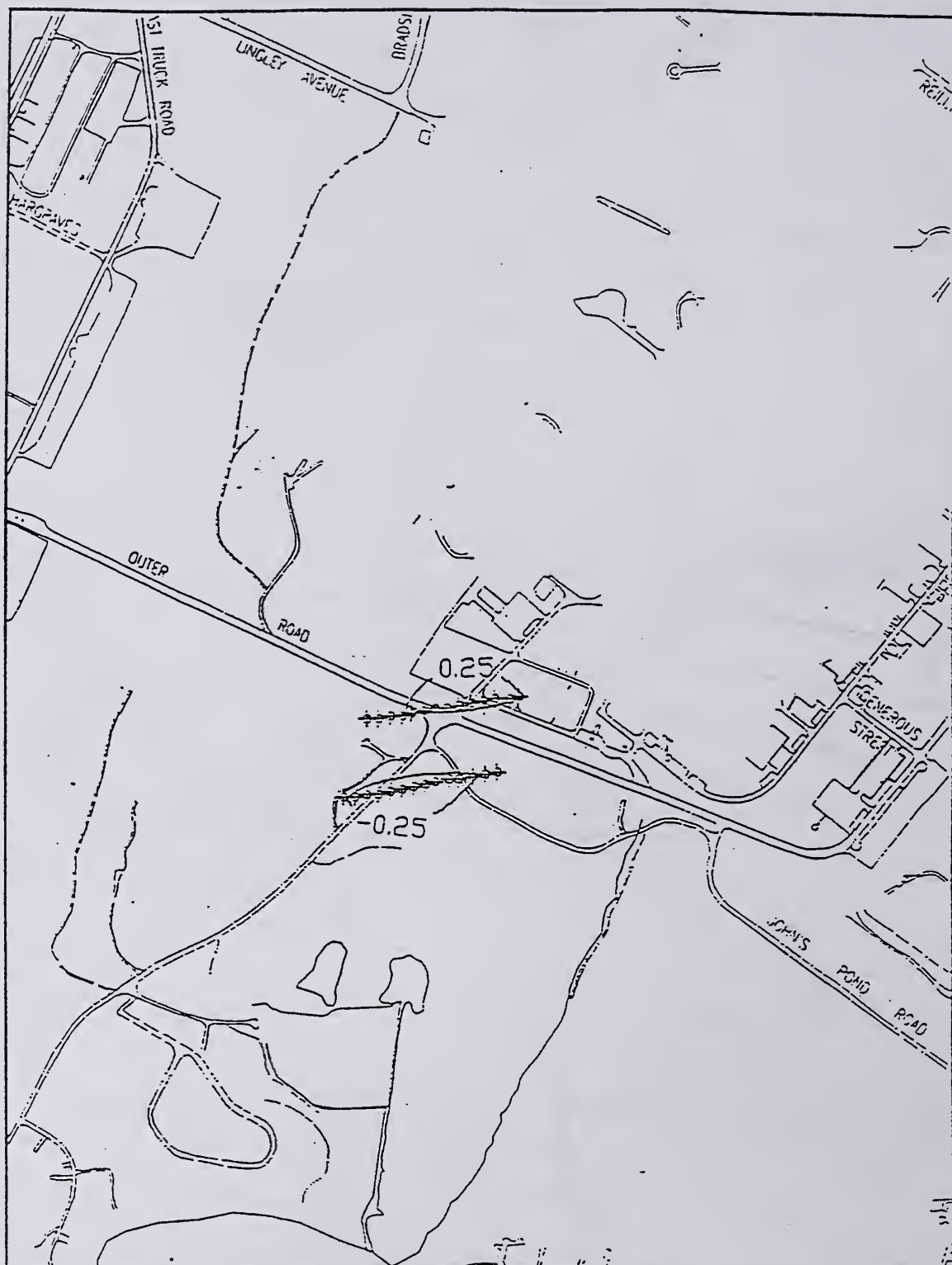
MMR SD-5 Scenario #5A Site Map

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: WLC
Checked by:
Drawing Name: SD5_S48.DWG
Project No.: OT WMR.01

Drawing No.

SD55a00



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MMR SD-5 Scenario #5A (350 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: WLC
Checked by:
Drawing Name: SD5_S43.DWG
Project No.: 01 MMR.G1

Drawing No.

SD55a02



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S05-5 Run #5A Pericles Ending At Walls

Massachusetts Military Reservation

Drawing Version No.: Rev 0
Drawn by: MLC
Checked by:
Drawing Name: S05_5A.DWG
Project No.: 07 MAP 01

Drawing No.

S05_5A



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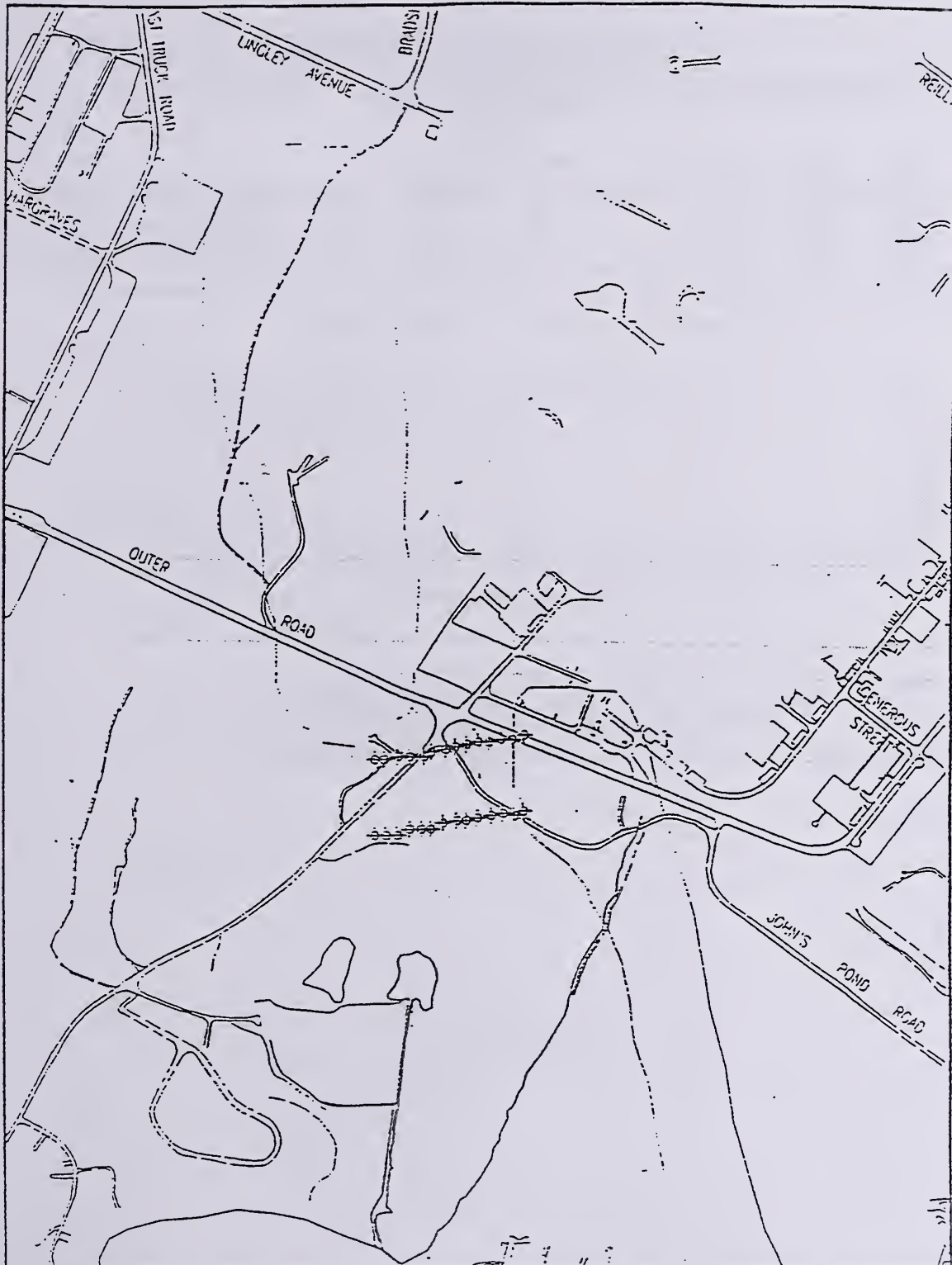
SD-5 Run #3A Particles Ending At A Boundary

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: ULC
Checked by:
Drawing Name: SDS_55A.DWG
Project No.: GT WWP 21

Drawing No.

SDS_5A



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MMR SD-5 Scenario #6 Site Map

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: WLS
Checked by:
Drawing Name: SD5_S5.DWG
Project No.: 07 MMR-01

Drawing No.

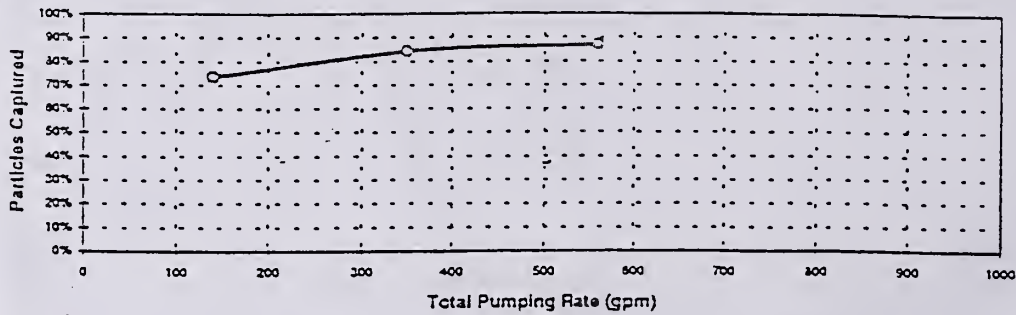
SD56 00

SD-5 Plume Containment System Performance: Scenario #6

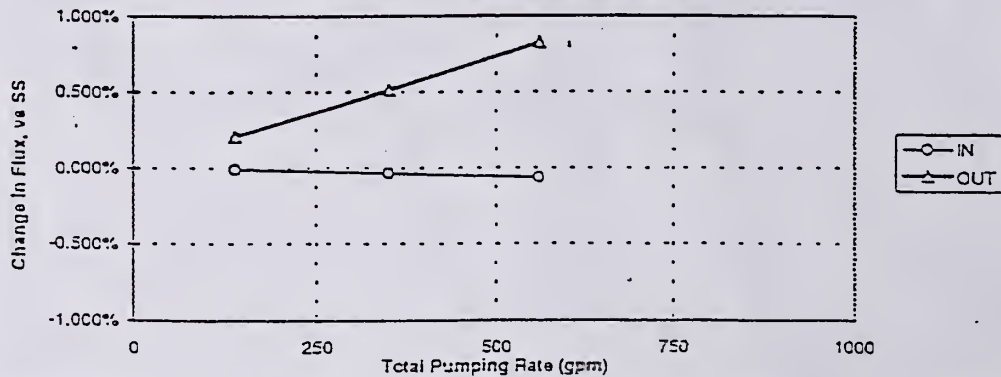
SD-5 Total Pump Rate (gpm)	SD-5 Plume: SD5NORTH.SED			WAF Plume: WAF.SED			Ashumet Pond Fluxes (cfs)			
	total particles	particles captured	percent captured	total particles	particles captured	percent captured	In:		Relative change vs. SS	Out: Relative change vs. SS
							In	Out		
-140	2948	2169	73.58%	789	209	26.49%	440778	-392244	-0.016%	0.204%
-350	2948	2483	84.23%	789	353	44.74%	440671	-393440	-0.041%	0.510%
-560	2948	2563	86.94%	789	394	49.94%	440556	-394674	-0.067%	0.825%

RUN 6A
RUN 6B
RUN 6C

SD-5 Scenario 6 Pumping Rates vs. % Capture SD5NORTH



Change in Flux Values Into and Out of Ashumet Pond
vs. Total Pumping Rate: Scenario 6



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MMR SD-5 PCS Scenario #6 Run 6A
Model Run Summary
5-18-96

Model: Constant head

Recharge = 29 in/yr

Nodes = 415298

Elements = 378828

Wells = 28

- 14 extraction wells (-10 gpm)
- 14 injection wells (10 gpm)
- TOTAL PUMP RATE = 140 GPM

Plume Particle Capture:

- SD5NORTH: 78.39% capture.
- SD5SOUTH: 0.32% capture.
- Western Aquifarm: 26.49% capture.
- PFSA: 0.00% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of the extraction fence.

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MEMR SD-5 PCS Scenario #6 Run 6B
Model Run Summary
5-18-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

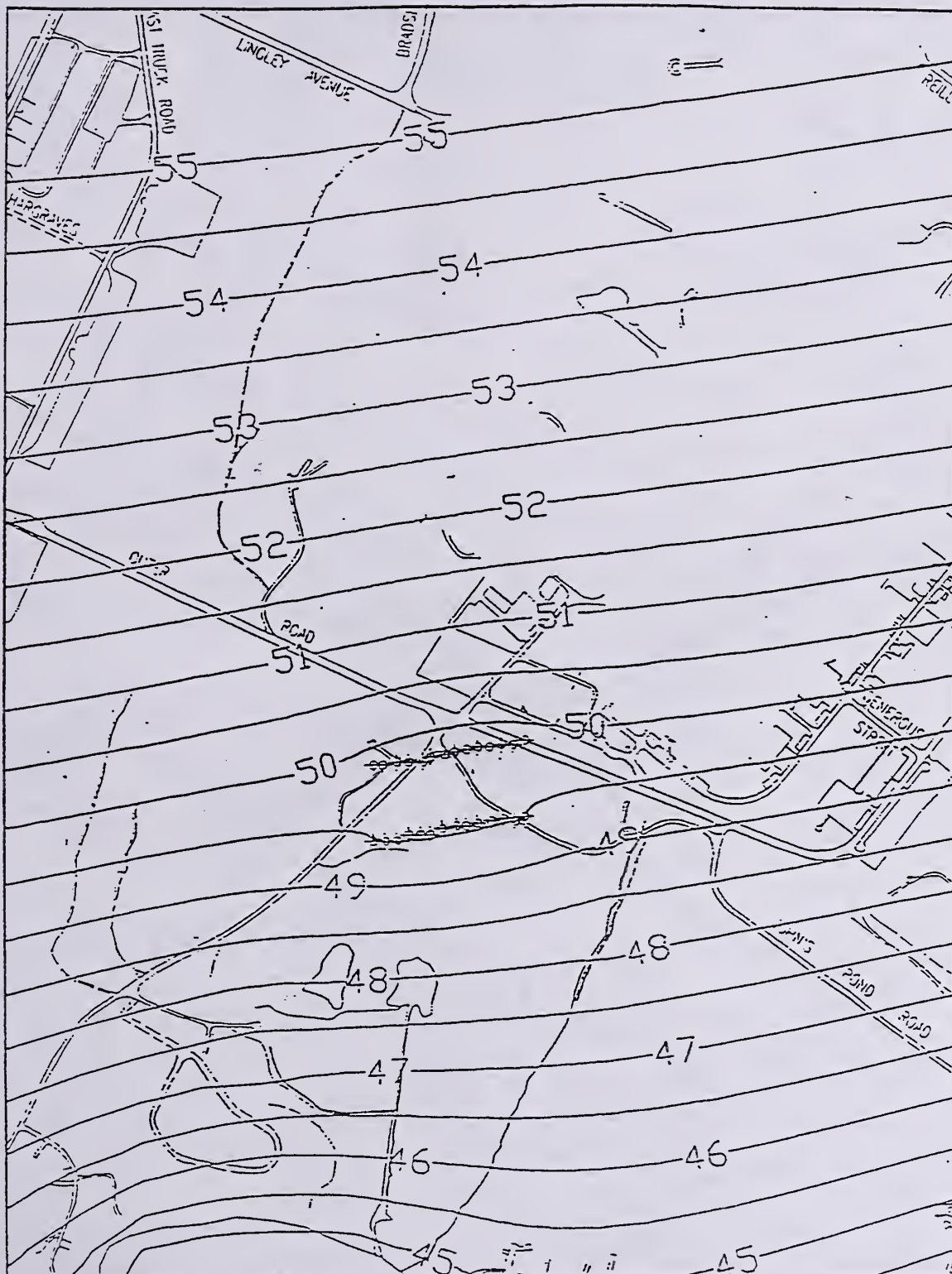
Wells = 28

- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Plume Particle Capture:

- SD5NORTH: 84.23% capture.
- SD5SOUTH: 2.27% capture.
- Western Aquifarm: 44.74% capture.
- PFSA: 0.09% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.



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MMR SD-5 Scenario #68 (350 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 3
 Drawn by: WLC
 Checked by:
 Drawing Name: SD5_Scenario
 Project No.: 01 MMR-01

Drawing No.

SD56b 01



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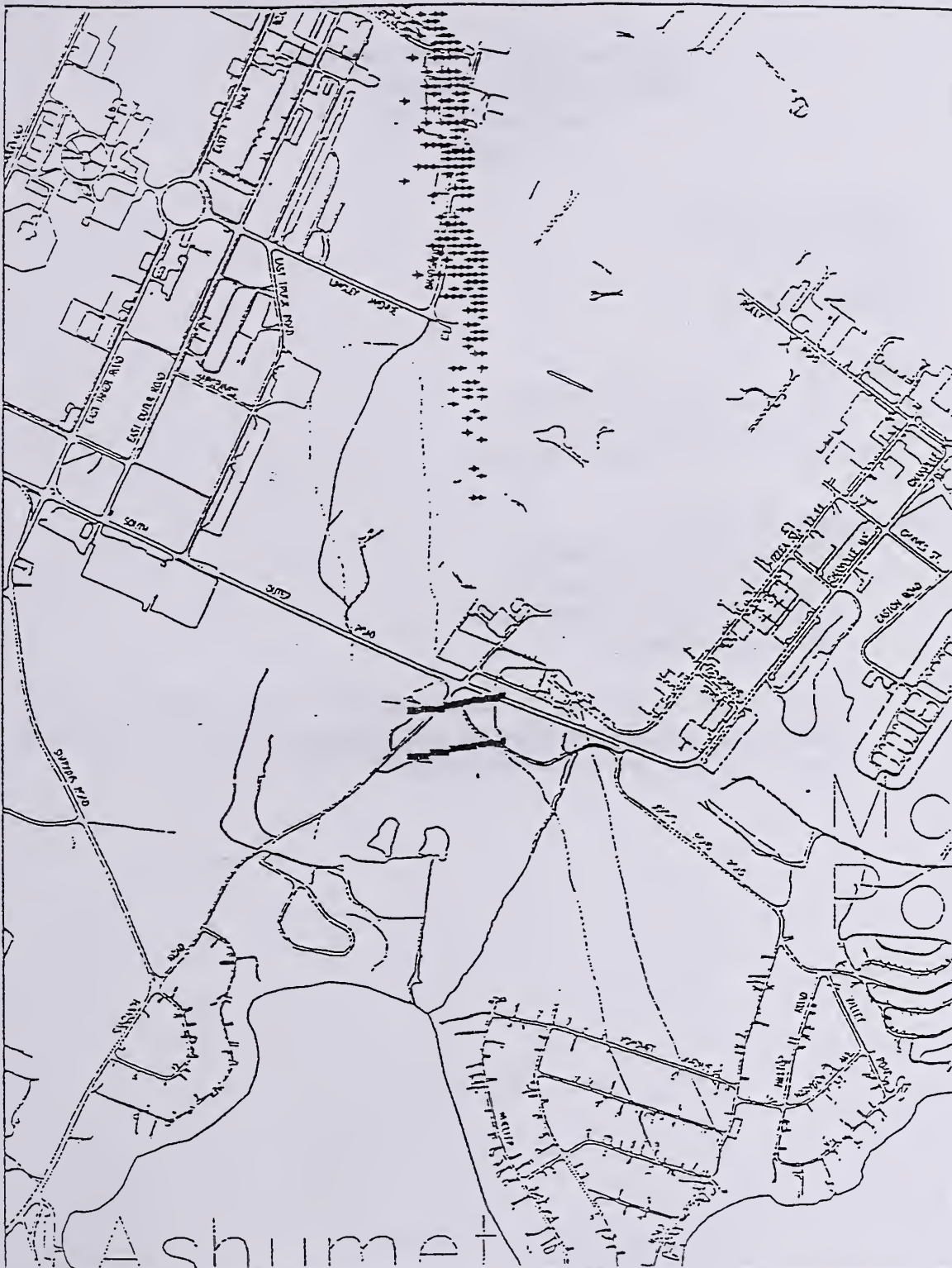
MMR SD-5 Scenario #68 (350 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD5_S06.DWG
Project No.: GT MMR01

Drawing No.

SD56b 02



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SD-5 Run 460 Parcels Ending At A Boundary

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: JLB
Checked by:
Drawing Name: SD5_000.DWG
Project No.: 00000000

Drawing No.
SD5_00

Environmental Consulting Engineers
MIMR SD-5 PCS Scenario #6 Run 6C
Model Run Summary
5-18-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

- 14 extraction wells (-40 gpm)
- 14 injection wells (40 gpm)
- TOTAL PUMP RATE = 560 GPM

Plume Particle Capture:

- SD5NORTH: 95.52% capture.
- SD5SOUTH: 2.51% capture.
- Western Aquifarm: 49.94% capture.
- PFSA: 0.72% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient ($Y > 236570$) of this line.

ATTACHMENT C

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 7B
Model Run Summary
5-22-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28
- 14 extraction wells (-25 gpm)
- 14 injection wells (25 gpm)
- TOTAL PUMP RATE = 350 GPM

Plume Particle Mass Capture:
- SD5NORTH: 86.23% capture.
- SD5SOUTH: 7.23% capture.
- Western Aquifarm: 64.01% capture.
- PFSA: 0.44% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 7D
Model Run Summary
5-22-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

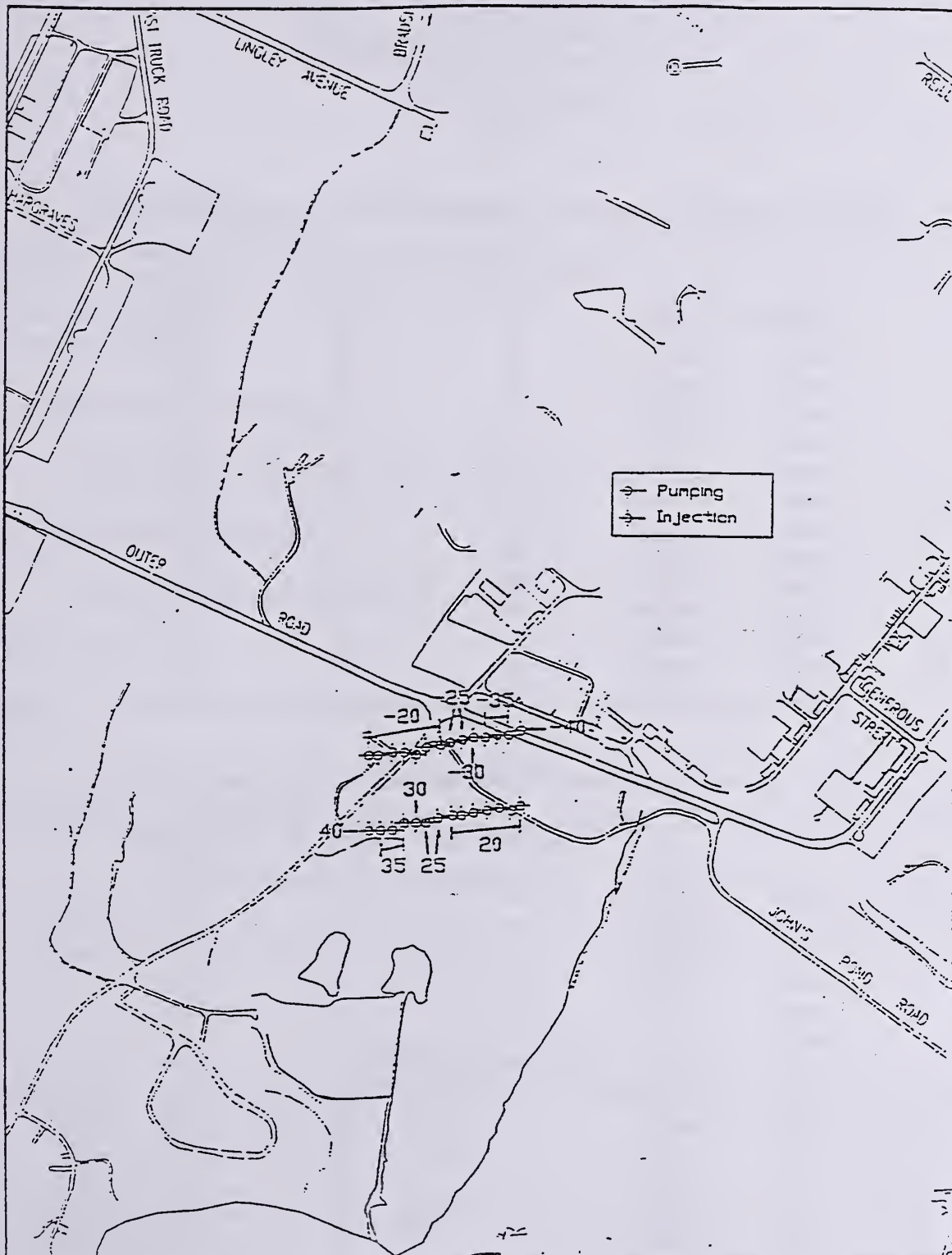
- 3 extraction wells (-35 gpm)
- 8 extraction wells (-25 gpm)
- 3 extraction wells (-20 gpm)
- 14 injection wells (26.07 gpm)
- TOTAL PUMP RATE = 365 GPM

Plume Particle Mass Capture:

- SD5NORTH: 86.96% capture.
- SD5SOUTH: 6.90% capture.
- Western Aquifer: 64.64% capture.
- PFSA: 0.54% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.

ATTACHMENT D



Environmental Consulting Engineers



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SD-5 Scenario & Well Locations and Constant Head Optimized Pumping Rates

Massachusetts Military Reservation

Drawing Version No.: Rev. 2
Drawn by: JMD
Checked by: VLG
Drawing Name: SD582M53MG
Project No.: 01 MUR.C1

Drawing No.

6.0621.01

SD-5 Constant Head Model PCS Scenario 6 Extraction Wells (-395 gpm)

Easting	Northing	Bottom of Screen (ft msl)	Top of Screen (ft msl)	Pump Rate (gpm)
864620	236220	-40	20	-20.00
864660	236220	-40	20	-20.00
864720	236230	-40	20	-20.00
864770	236230	-40	20	-20.00
864830	236230	-40	20	-20.00
864860	236250	-40	20	-20.00
864920	236260	-40	20	-20.00
864960	236270	-40	20	-25.00
865010	236280	-40	20	-30.00
865060	236290	-40	20	-35.00
865110	236290	-40	20	-35.00
865160	236300	-40	20	-40.00
865210	236300	-40	20	-40.00
865260	236320	-40	20	-50.00

SD-5 Constant Head Model PCS Scenario 6 Injection Wells (395 gpm)

Easting	Northing	Bottom of Screen (ft msl)	Top of Screen (ft msl)	Pump Rate (gpm)
864620	235900	-40	20	50.00
864670	235900	-40	20	40.00
864720	235900	-40	20	40.00
864770	235925	-40	20	35.00
864820	235925	-40	20	35.00
864860	235925	-40	20	30.00
864910	235950	-40	20	25.00
864970	235960	-40	20	20.00
865010	235960	-40	20	20.00
865060	235970	-40	20	20.00
865120	235980	-40	20	20.00
865170	235990	-40	20	20.00
865220	235980	-40	20	20.00
865260	236000	-40	20	20.00

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 8
Model Run Summary
6-7-96

Model: Constant head

Description: ECE defined inputs with 100% recharge, 100% K field, and 100% pumping rate.

Recharge = 29 in/yr

K Field = ECE defined.

Nodes = 415298

Elements = 378828

Extraction Wells = 14 (-395 gpm)

- fence: -50x1, -40x2, -35x2, -30x1, -25x1, -20x7 gpm

Injection Wells = 14 (395 gpm)

- fence: 50x1, 40x2, 35x2, 30x1, 25x1, 20x7 gpm

Plume Capture:

Mass:

Lower Bound Calculation

Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	3312	79.31%
2.4	1033	2479.2	2152.8	86.83%
1.2	1400	1680	1516.8	90.29%
<i>totals</i>	2607	8335.2	6981.6	83.76%

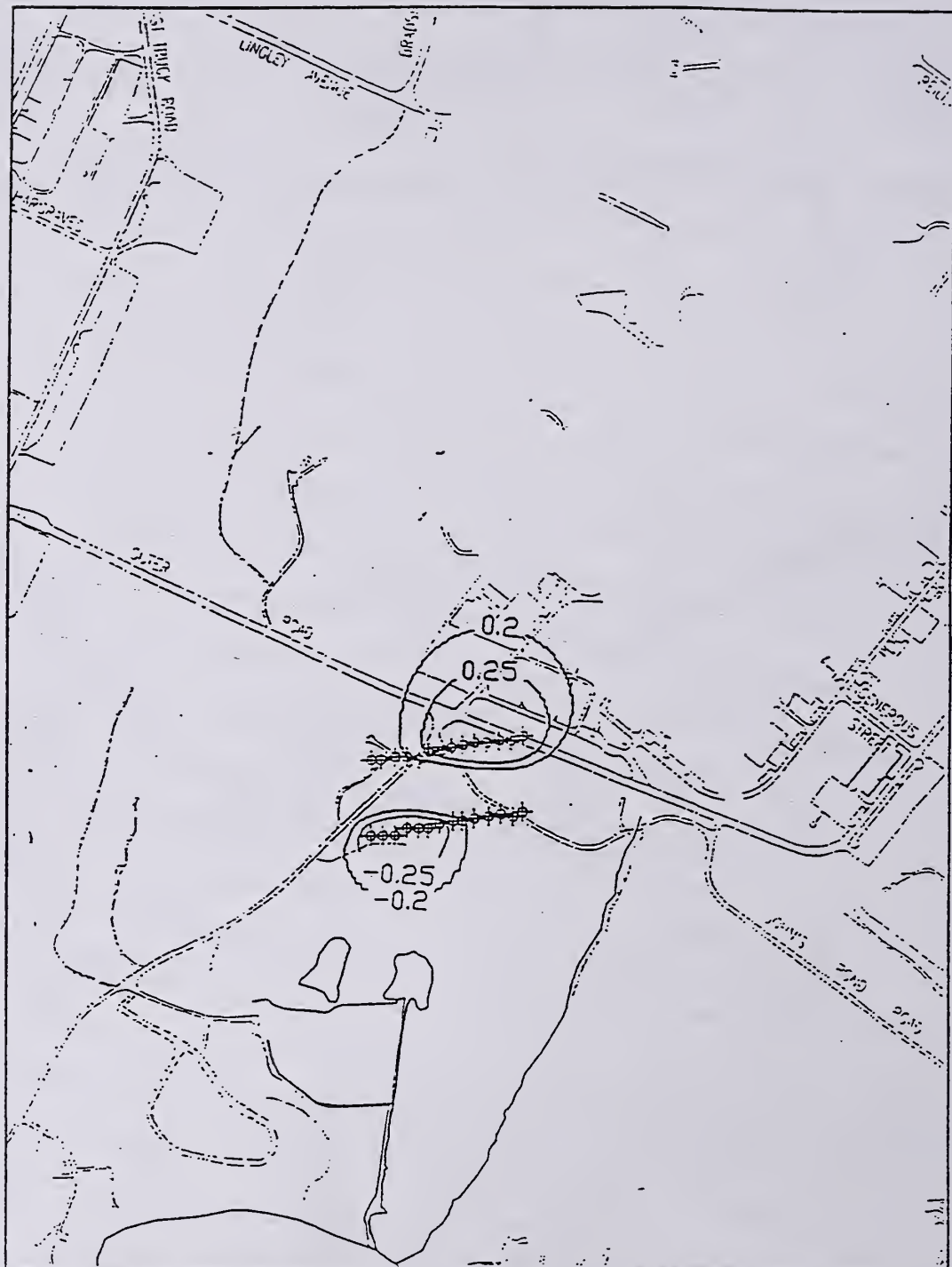
Upper Bound Calculation

Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	33120	79.31%
24	1033	24792	21528	86.83%
2.4	1400	3360	3033.6	90.29%
<i>totals</i>	2607	69912	57681.6	82.51%

Volume:

Associated Volume (ft ³)*	# of Particles	Total Volume (ft ³)	Captured Volume (ft ³)	% Volume Captured
8,750	2607	22,811,250	20,116,250	88.19%

* Associated volume reported as the total volume associated with each particle (25,000 ft³) multiplied by the porosity ($n=0.35$)



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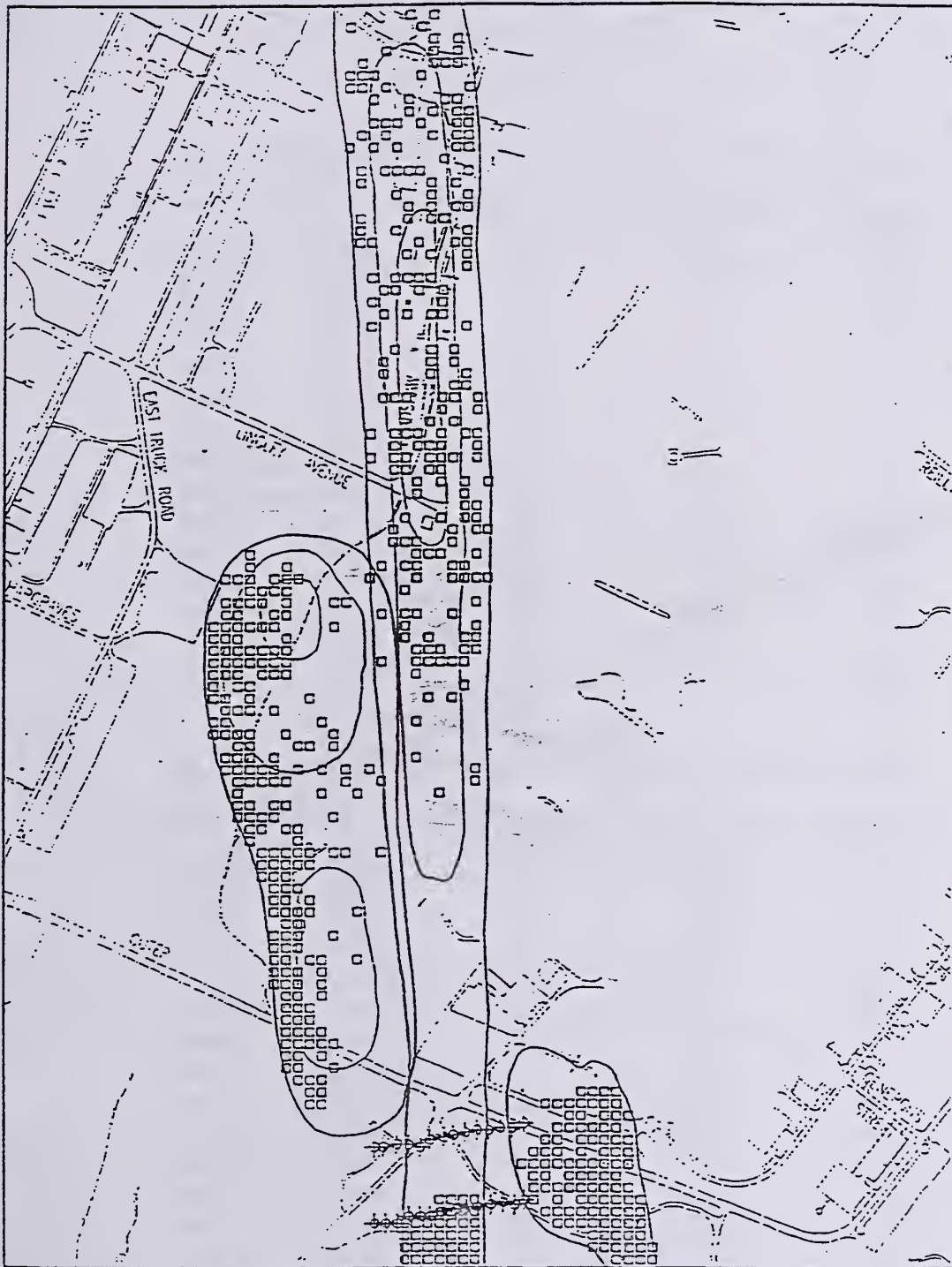
SD-5 Scenario 6 Run 8 (395 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: BTH
 Checked by: WLC
 Drawing Name: SD58WT.DWG
 Project No.: QT WMR.01

Drawing No.

S6.08.CD



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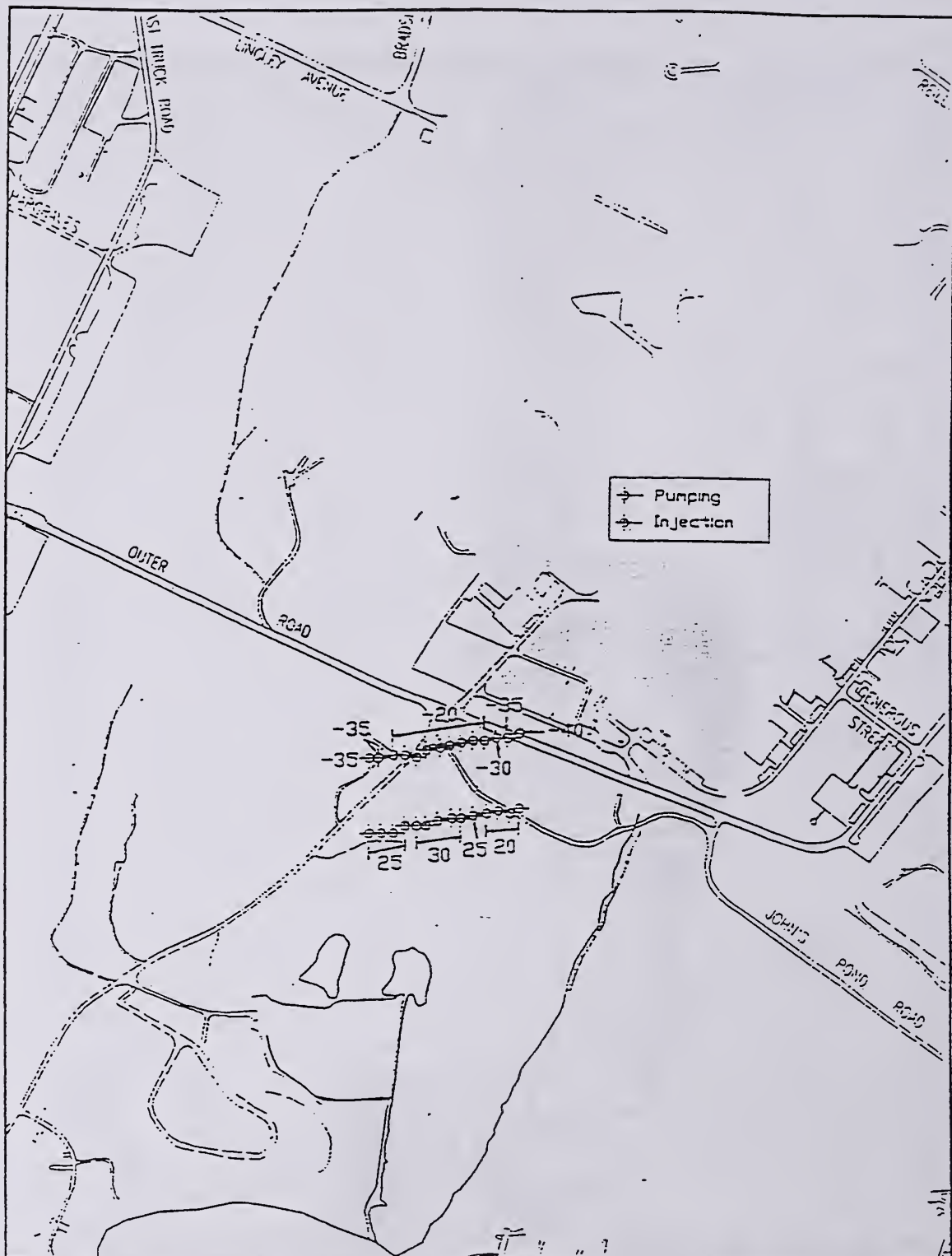
SD-5 Scenario 5 Run 8 (CH) Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD5CHPS.DWG
Project No.: 07 WMR 01

Drawing No.

S6.08.CH



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SD-5 Scenario 5 Well Locations and High X Optimized Pumping Rates

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: JKO
Checked by: MLC
Drawing Name: SD581WLS.DWG
Project No.: 01 MMR-01

Drawing No.

S6.1.00

SD-5 High K Model PCS Scenario 6 Extraction Wells (-355gpm)

Easting	Northing	Bottom of Screen (ft msl)	Top of Screen (ft msl)	Pump Rate (gpm)
864620	236220	-40	0	-35.00
864660	236220	-40	0	-35.00
864720	236230	-40	0	-20.00
864770	236230	-40	0	-20.00
864820	236220	-40	0	-20.00
864860	236250	-40	0	-20.00
864920	236260	-40	0	-20.00
864960	236270	-40	0	-20.00
865010	236280	-40	0	-20.00
865060	236290	-40	0	-20.00
865110	236290	-40	0	-20.00
865160	236300	-40	0	-30.00
865210	236300	-40	0	-35.00
865260	236320	-40	0	-40.00

SD-5 High K Model PCS Scenario 6 Injection Wells (355 gpm)

Easting	Northing	Bottom of Screen (ft msl)	Top of Screen (ft msl)	Pump Rate (gpm)
864620	235900	-20	20	25.00
864670	235900	-20	20	25.00
864720	235900	-20	20	25.00
864770	235930	-20	20	25.00
864820	235930	-20	20	30.00
864860	235930	-20	20	30.00
864910	235950	-20	20	30.00
864970	235960	-20	20	30.00
865010	235960	-20	20	30.00
865060	235970	-20	20	25.00
865120	235980	-20	20	20.00
865170	235990	-20	20	20.00
865220	235980	-20	20	20.00
865260	236000	-20	20	20.00

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 8
Model Run Summary
6-7-96

Model: Constant head

Description: ECE defined inputs with 100% recharge, 100% K field, and 100% pumping rate.

Recharge = 29 in/yr

K Field = ECE defined.

Nodes = 415298

Elements = 378828

Extraction Wells = 14 (-395 gpm)

- fence: -50x1, -40x2, -35x2, -30x1, -25x1, -20x7 gpm

Injection Wells = 14 (395 gpm)

- fence: 50x1, 40x2, 35x2, 30x1, 25x1, 20x7 gpm

Plume Capture:

Mass:

Lower Bound Calculation

Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	3312	79.31%
2.4	1033	2479.2	2152.8	86.83%
1.2	1400	1680	1516.8	90.29%
<i>totals</i>	2607	8335.2	6981.6	83.76%

Upper Bound Calculation

Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	33120	79.31%
24	1033	24792	21528	86.83%
2.4	1400	3360	3033.6	90.29%
<i>totals</i>	2607	69912	57681.6	82.51%

Volume:

Associated Volume (ft ³) *	# of Particles	Total Volume (ft ³)	Captured Volume (ft ³)	% Volume Captured
8,750	2607	22,811,250	20,116,250	88.19%

* Associated volume reported as the total volume associated with each particle (25,000 ft³) multiplied by the porosity ($n=0.35$)

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 9
Model Run Summary
6-7-96

Model: Constant head

Description: ECE defined inputs with 100% recharge, 100% K field, and 100% pumping rate.

Recharge = 29 in/yr

K Field = ECE defined.

Nodes = 415298

Elements = 378828

Extraction Wells = 14 (-365 gpm)

- fence: -40x1, -35x3, -30x1, -25x2, -20x7 gpm

Injection Wells = 14 (365 gpm)

- fence: 40x1, 35x3, 30x1, 25x2, 20x7 gpm

Plume Capture:

Mass:

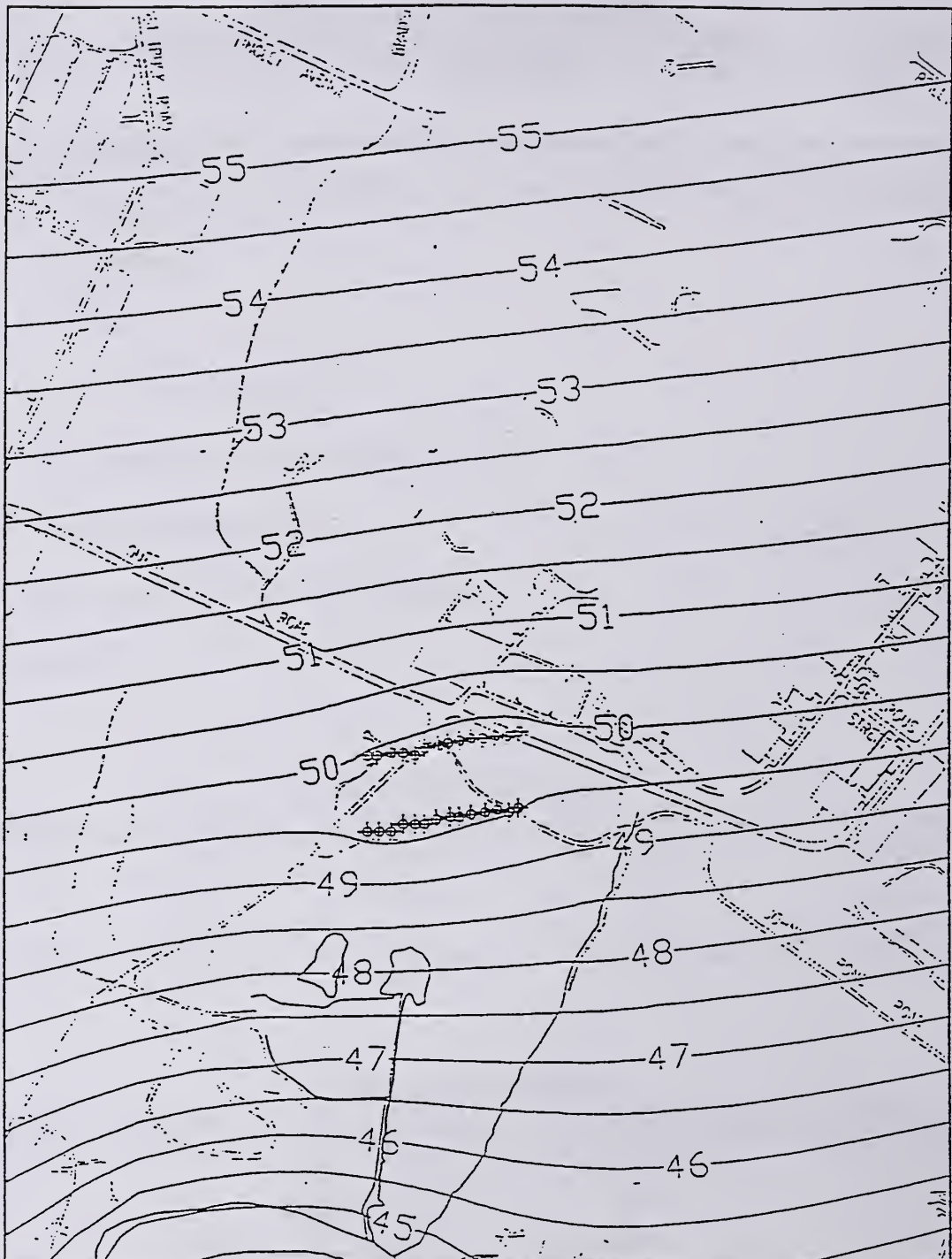
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	3168	75.86%
2.4	1033	2479.2	2172	87.61%
1.2	1400	1680	1516.8	90.29%
<i>totals</i>	2607	8335.2	6856.8	82.26%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	31680	75.86%
24	1033	24792	21720	87.61%
2.4	1400	3360	3033.6	90.29%
<i>totals</i>	2607	69912	56433.6	80.72%

Volume:

Associated Volume (ft ³)*	# of Particles	Total Volume (ft ³)	Captured Volume (ft ³)	% Volume Captured
8,750	2607	22,811,250	20133750	88.26%

* Associated volume reported as the total volume associated with each particle (25,000 ft³) multiplied by the porosity ($n=0.35$)



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SD-3 Scenario 6 Run 9 (363 gpm) Watertable

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD36WT.DWG
Project No.: 01 MMR.01

Drawing No.

S6.09.CW

Environmental Consulting Engineers
MMR SD-5 Scenario #6 Run 10
Model Run Summary
6-12-96

Model: High K Box Model
Description: Optimization
Recharge = 27 in/yr
K Field = ECE defined.
Nodes = 772421
Elements = 707112

Extraction Wells = 14 (-355 gpm)
- fence: -35x2, -20x9, -30, -35, -40 gpm
- screen interval -40 to 20 ft msl

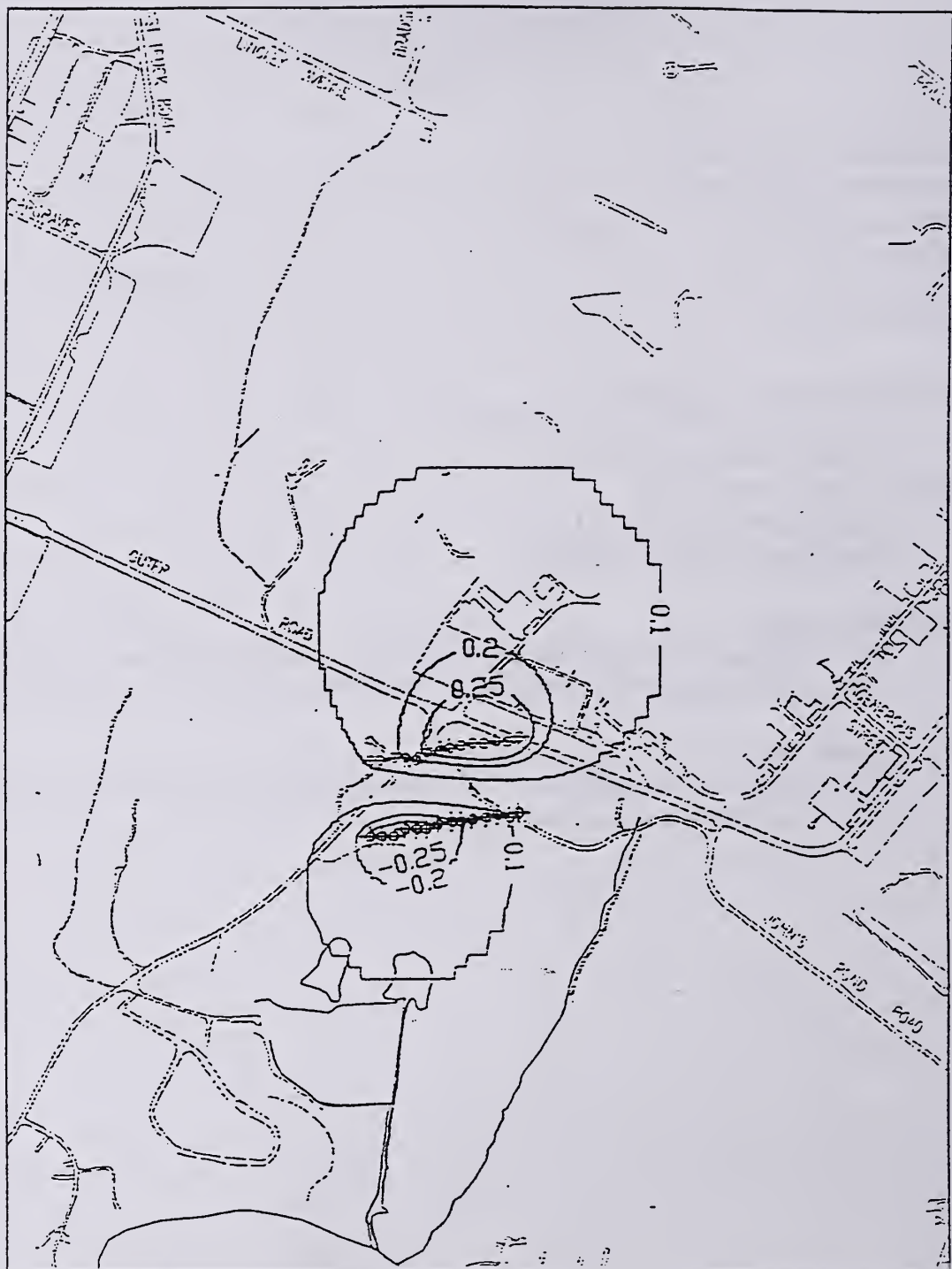
Injection Wells = 14 (355 gpm)
- fence: 25x4, 30x5, 25, 20x4 gpm
- screen interval -40 to 20 ft msl.

SD-5 Plume Capture:

This configuration resulted in Insufficient capture of the SD-5 Chlorinated VOC plume.
Portions of the plume travel south past the extraction fence and over the extraction fence.

Recommendations:

Raise the injection well screen interval to assist in the development of steep gradients north towards the extraction wells.



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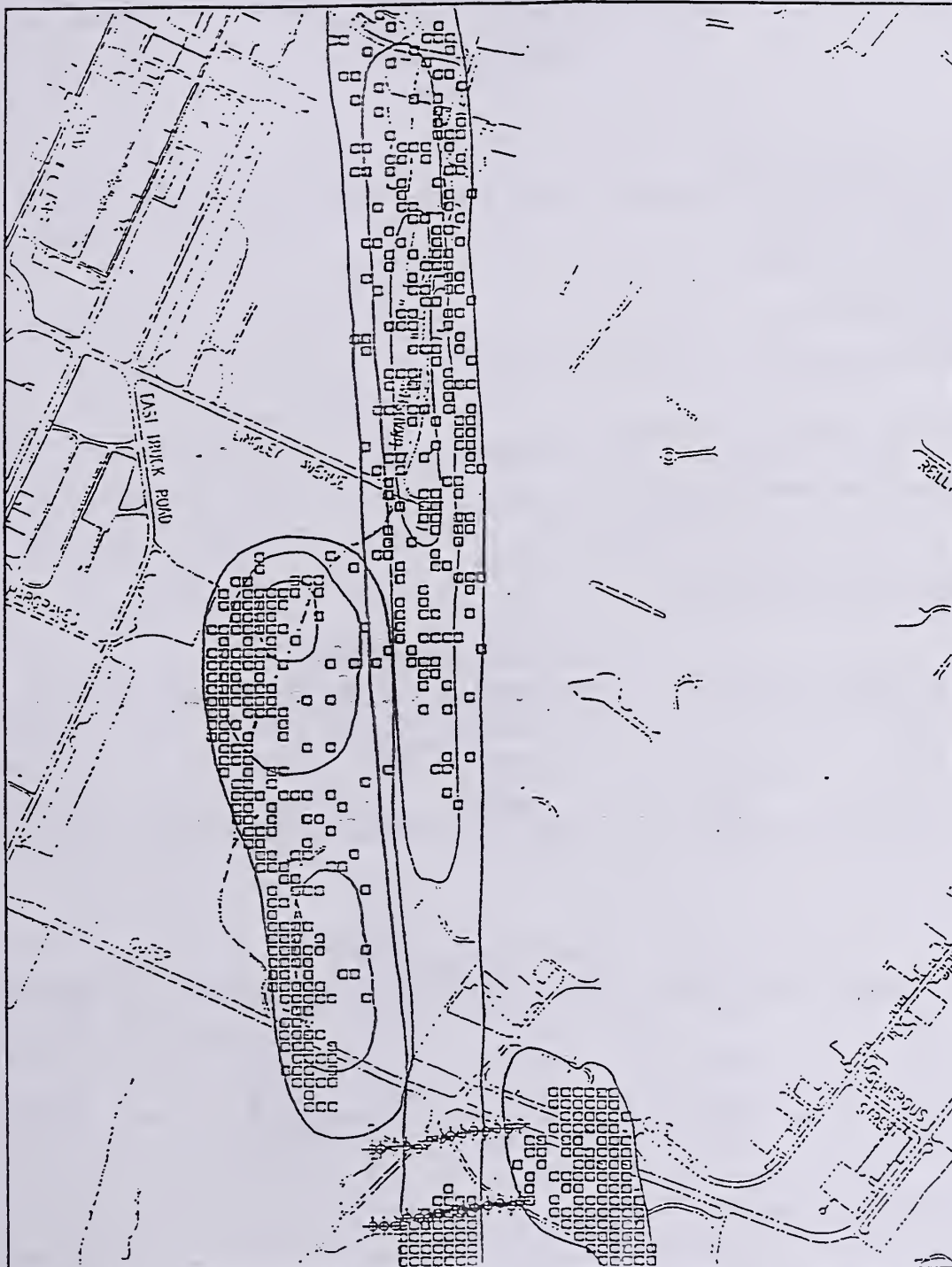
P.O. Box 22568
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SD-3 Scenario 2 Run 9 (355 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version: Rev. 2
Drawn by: BRP
Checked by: VLG
Drawing Name: SD3DWT.DWG
Printed by: 07/10/07

Drawing No.
SS.09.CD



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Fax: (423) 657-6571

SD-S Scenario 5 Run 9 (CH) Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD9CHP9.DWG
Project No.: CT MMR-01

Drawing No.

S6.09.CH

Environmental Consulting Engineers
MMR SD-5 100/100/100
Model Run Summary
6-12-96

Model: High K Box Model

Description: ECE defined inputs with 100% K field, 100% recharge, and 100% pumping rate.

Recharge = 27 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN1

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

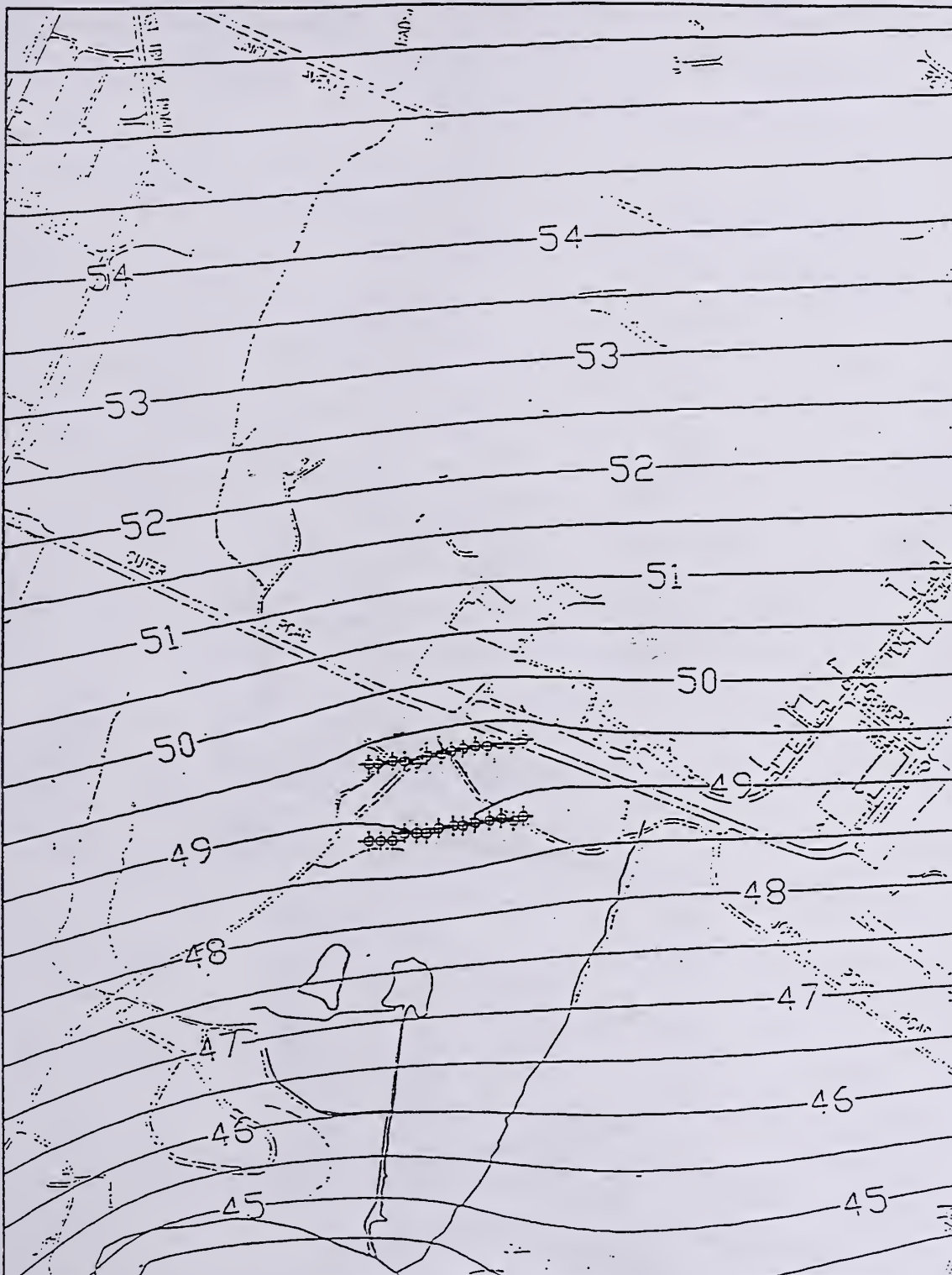
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4104	98.28%
2.4	1033	2479.2	2450.4	98.84%
1.2	1400	1680	1664.4	99.07%
<i>totals</i>	2607	8335.2	8218.8	98.60%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41040	98.28%
24	1033	24792	24504	98.84%
2.4	1400	3360	3328.8	99.07%
<i>totals</i>	2607	69912	68872.8	98.51%

Plume Capture Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,566,250	98.93%

* Volume of water per particle using porosity of 35%



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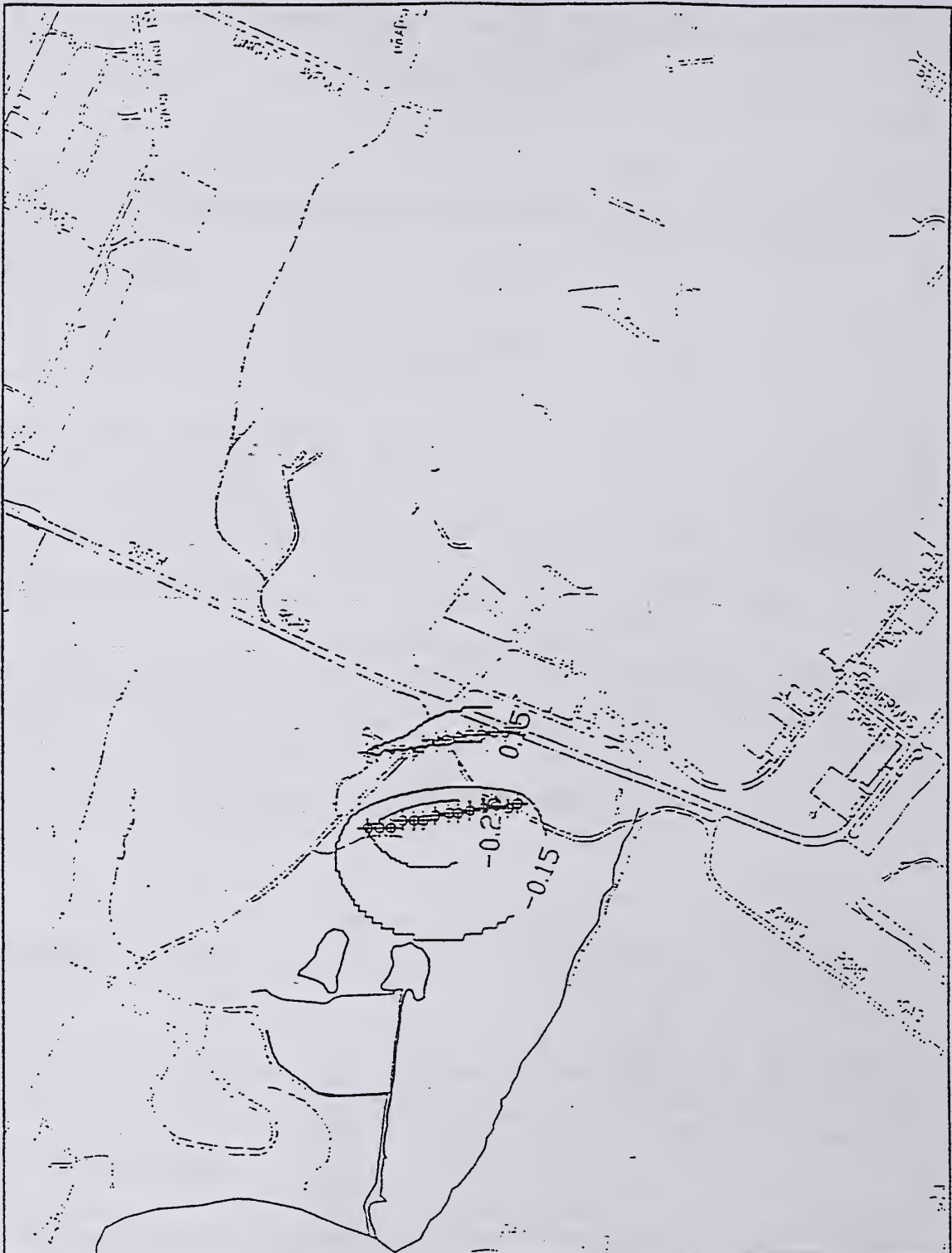
Phone: (423) 691-3668
Fax: (423) 691-0671

SD-5 Scenario 5 Run 1 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD551WT.DWG
Project No.: 07 WMR.01

Drawing No.
S6.1.01



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SD-5 Scenario 6 Run 1 (355 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLC
Drawing Name: SD56100.DWG
Project No.: 07 UMR.01

Drawing No.

S6.1.02



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Phone: (423) 691-3666
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SD-5 Scenario 6 Run 1 Particles Ending At Boundaries

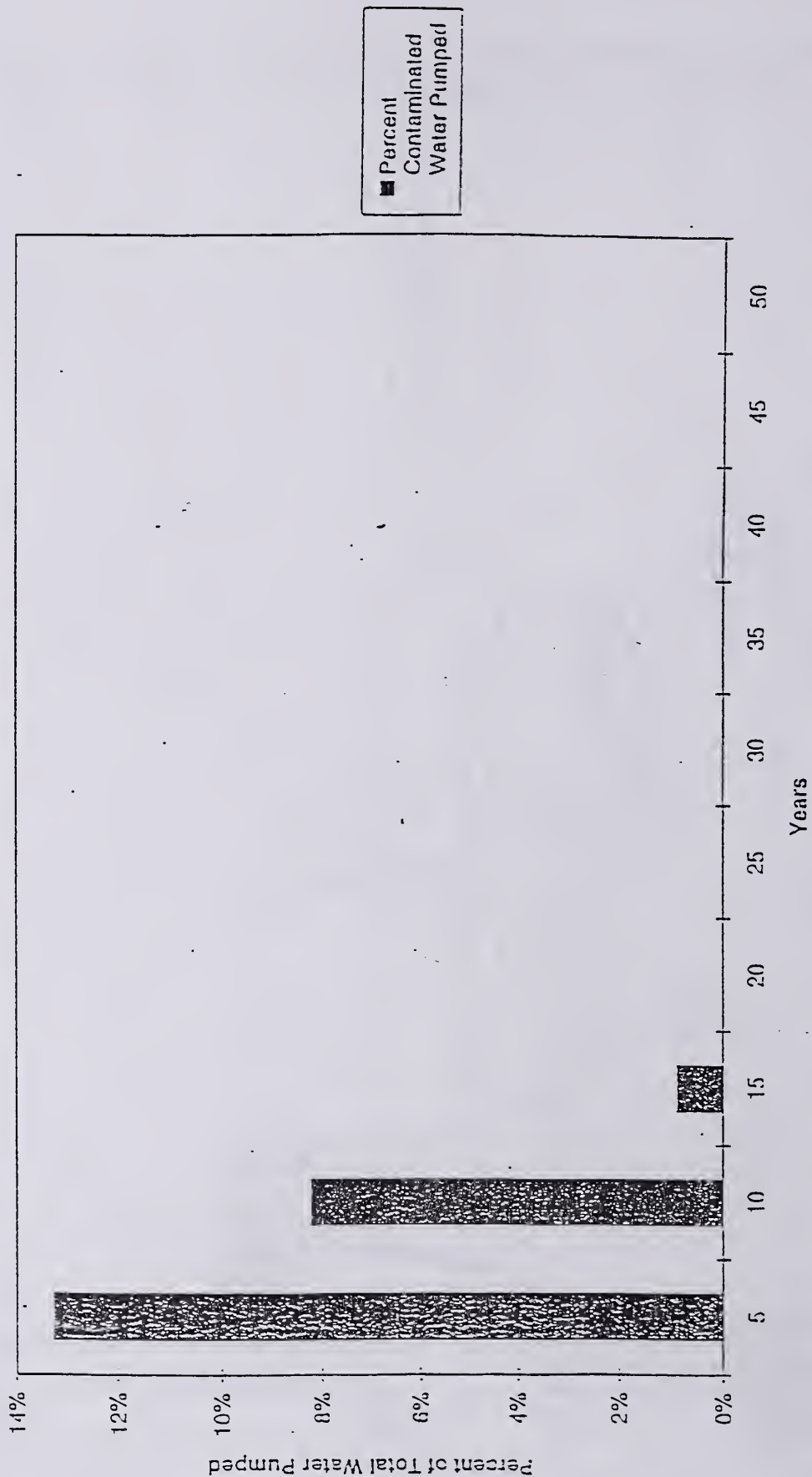
Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: MLC
Checked by:
Drawing Name: SD561PB.DWG
Project No.: 01 UMR.01

Drawing No.

S6.1.03

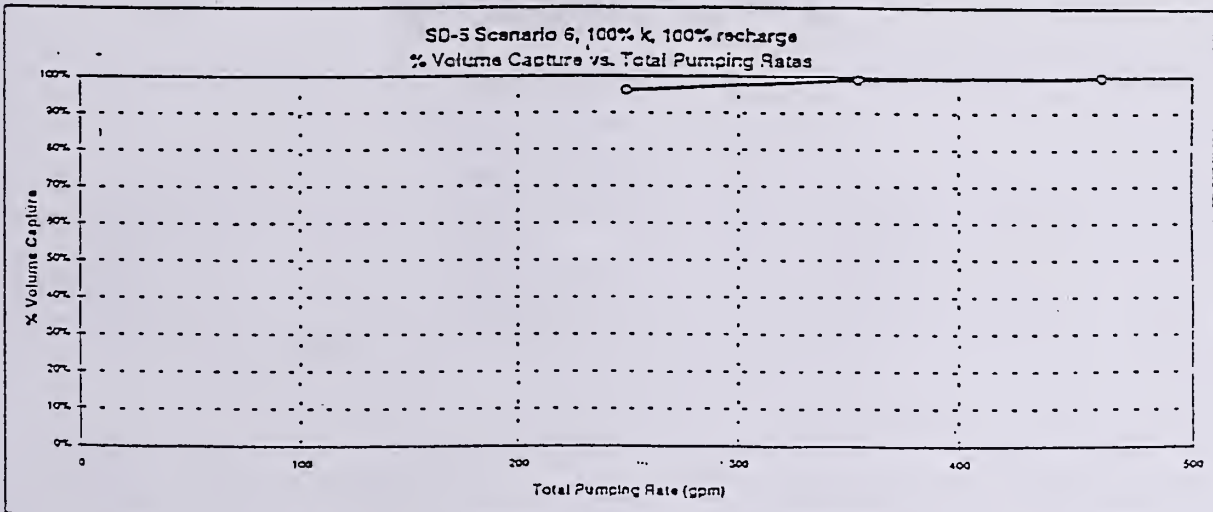
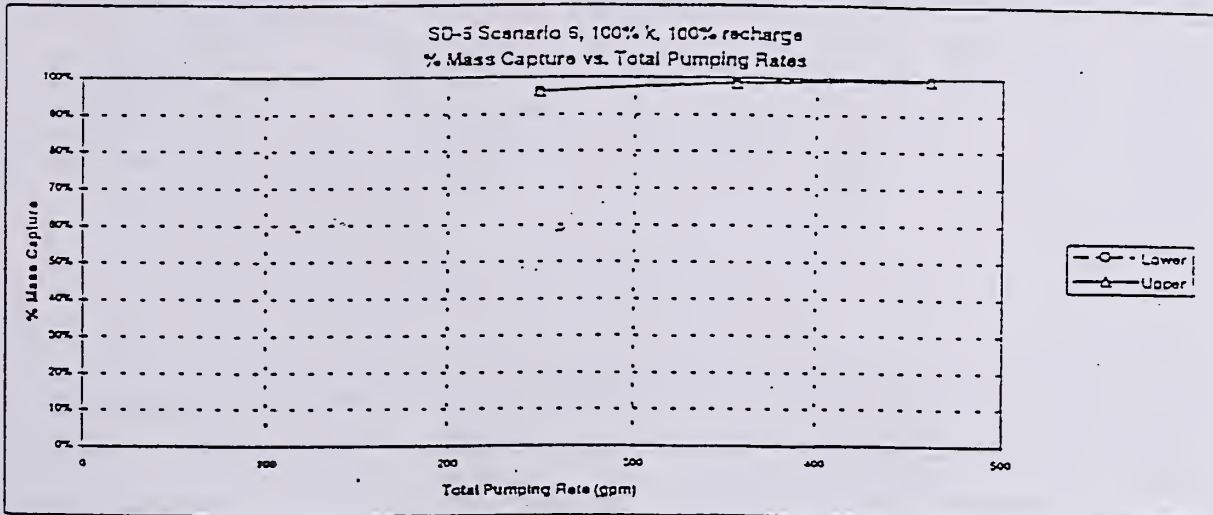
SD-5 System: Makeup of Pumped Water vs. Time*
 Contaminated Water Pumped as Percent of Total Water Pumped



* SD-5 Contaminated Water is defined as water within the 5 ppb Isoconcentration contour of Chlorinated VOCs in the Data Gap Field Work Technical Memorandum (OpTech, 1996)

SD-5 Plume Containment System Performance: 100/100/#

Run ID	Pump rate (cpm)	SD-5 Plume									
		Total particles	Particles captured	Percent particles captured	Total mass, Lower Bound (micrograms)	Mass captured, Lower Bound (micrograms)	Percent mass captured, Lower Bound	Total mass, Upper Bound (micrograms)	Mass captured, Upper Bound (micrograms)	Percent mass captured, Upper Bound	Percent volume captured
SS	0										
RUN2	248.5	2607	2505	96.09%	8335.2	8013	96.20%	65912	67205	96.13%	96.09%
RUN1	355	2607	2579	98.93%	8335.2	8219	98.50%	65912	68873	98.51%	98.93%
RUN3	461.5	2607	2597	99.62%	8335.2	8275	99.29%	65912	69370	99.22%	99.62%



ATTACHMENT E

MMR SD-5 Groundwater Model Sensitivity/Uncertainty Analysis
Migration of Contaminated Water in High Conductivity (K) Pond and Constant Head Pond Model Runs
Environmental Consulting Engineers

High K Pond results listed below are based on a total pumping rate of 355 gpm and 100% recharge = 27 In/yr

Constant Head Ponds runs were completed only for the 100/100/100 conditions

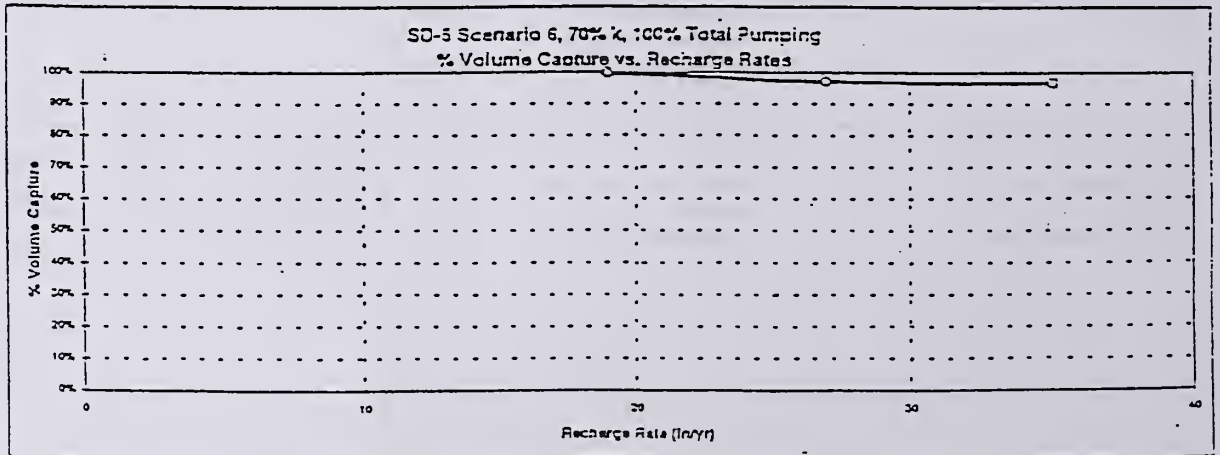
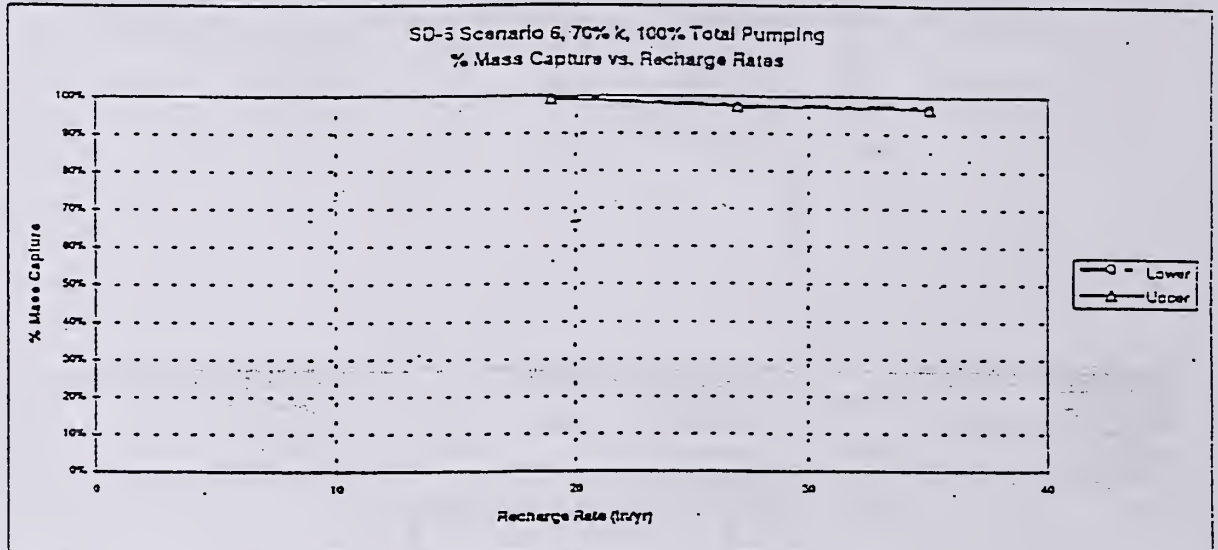
Constant Head Ponds results listed below are based on a total pumping rate of 365 gpm and 100% recharge = 29 In/yr
 Upper Bound % Mass Capture values are derived from particle mass values greater than the provided data indicate
 Lower Bound % Mass Capture values are derived from particle mass values less than the provided data indicate

		Recharge			
		70%		100%	
				120%	
High K Pond	% Mass Capture, High K Ponds, Upper Bound	99.09%		% Mass Capture, High K Ponds, Upper Bound	96.82%
	% Mass Capture, High K Ponds, Lower Bound	99.18%		% Mass Capture, High K Ponds, Lower Bound	96.70%
	% Volume Capture, High K Ponds	99.50%		% Volume Capture, High K Ponds	96.52%
Constant Head Ponds	% Mass Capture, High K Ponds, Upper Bound	96.70%		% Mass Capture, High K Ponds, Upper Bound	98.57%
	% Mass Capture, High K Ponds, Lower Bound	96.86%		% Mass Capture, High K Ponds, Lower Bound	98.59%
	% Volume Capture, High K Ponds	97.62%		% Volume Capture, High K Ponds	98.31%
	% Mass Capture, Constant Head Ponds, Upper Bound		80.72%		
	% Mass Capture, Constant Head Ponds, Lower Bound		82.25%		
	% Volume Capture, Constant Head Ponds		88.25%		
	% Mass Capture, High K Ponds, Upper Bound	98.91%		% Mass Capture, High K Ponds, Upper Bound	94.25%
	% Mass Capture, High K Ponds, Lower Bound	98.76%		% Mass Capture, High K Ponds, Lower Bound	94.53%
	% Volume Capture, High K Ponds	98.16%		% Volume Capture, High K Ponds	94.74%

130%

SD-5 Plume Containment System Performance: 70/#/100

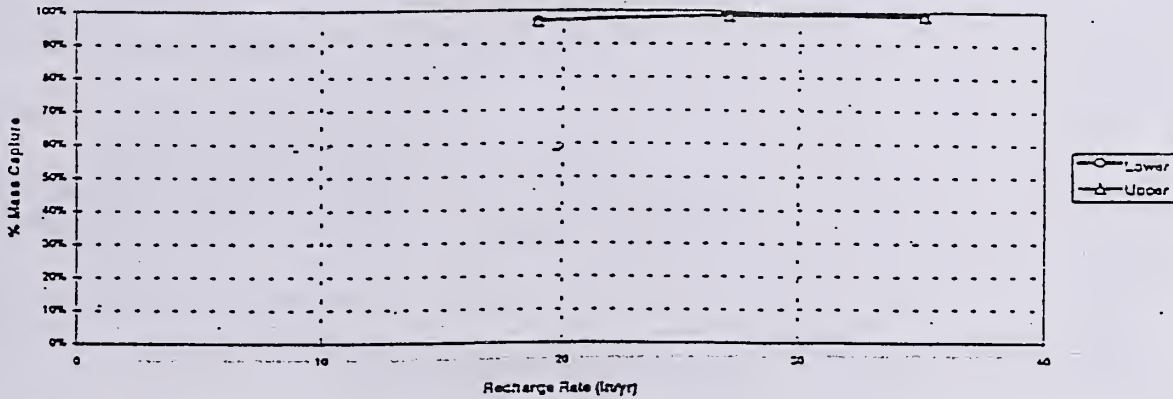
Run ID	Recharge (In/yr)	SD-5 Plume									
		Total particles	Particles captured	Percent particles captured	Total mass, Lower Bound (micrograms)	Mass captured, Lower Bound (micrograms)	Percent mass captured, Lower Bound	Total mass, Upper Bound (micrograms)	Mass captured, Upper Bound (micrograms)	Percent mass captured, Upper Bound	Percent volume captured
SS	27										
RUN6	18.9	2607	2594	99.50%	8335.2	8257	99.18%	65912	69276	99.09%	99.50%
RUN4	27	2607	2529	97.01%	8335.2	8100	97.18%	65912	68040	97.32%	97.01%
RUN10	35.1	2607	2519	96.62%	8335.2	8060	96.70%	65912	67692	96.62%	96.62%



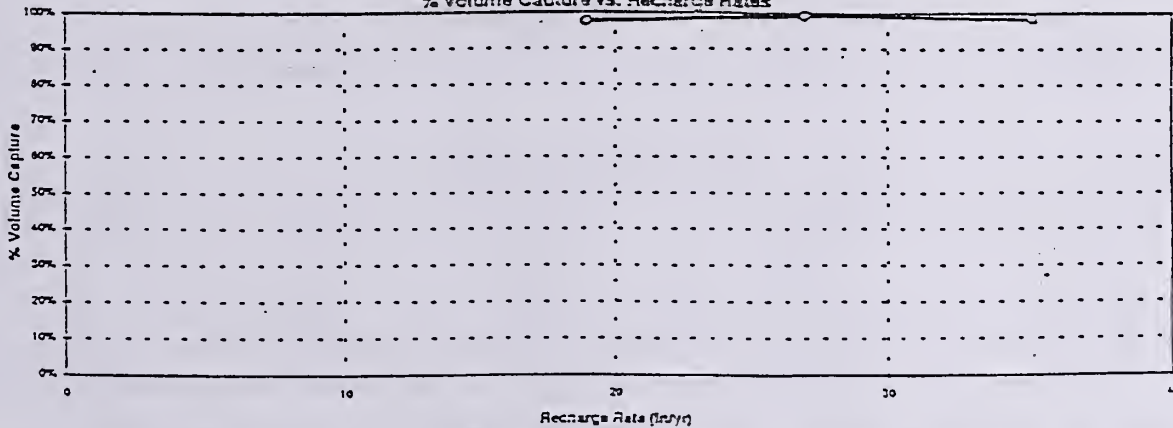
SD-5 Plume Containment System Performance: 100/#/100

Run ID	Recharge (lrvyr)	SD-5 Plume									
		Total particles	Particles captured	Percent particles captured	Total mass, Lower Bound (micrograms)	Mass captured, Lower Bound (micrograms)	Percent mass captured, Lower Bound	Total mass, Upper Bound (micrograms)	Mass captured, Upper Bound (micrograms)	Percent mass captured, Upper Bound	Percent volume captured
SS	27										
RUN8	18.9	2607	2545	97.62%	8335.2	8074	96.86%	65912	67603	96.70%	97.62%
RUN1	27	2607	2579	98.93%	8335.2	8219	98.60%	65912	68873	98.51%	98.93%
RUN11	35.1	2607	2563	98.31%	8335.2	8218	98.59%	65912	68986	98.57%	98.31%

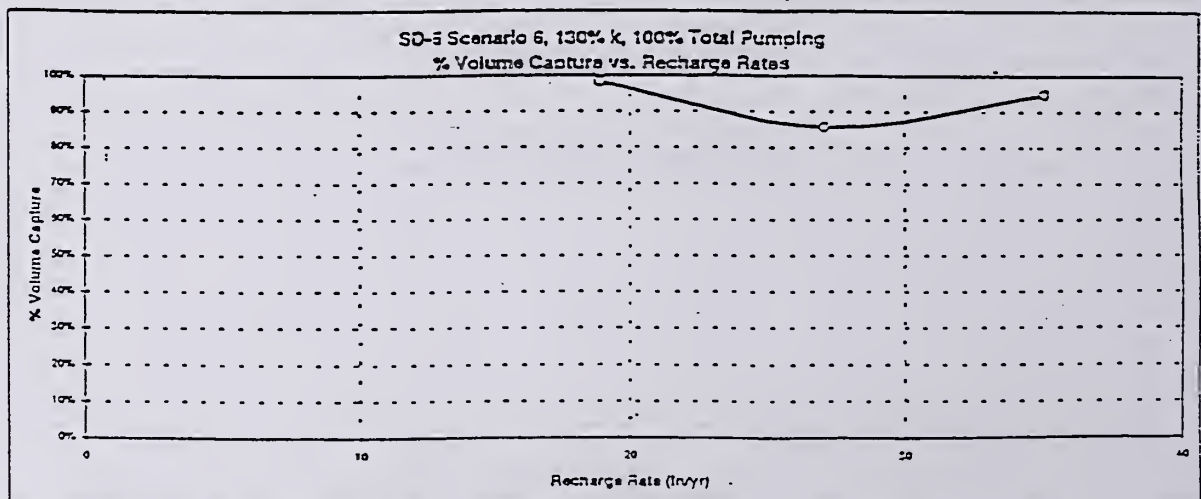
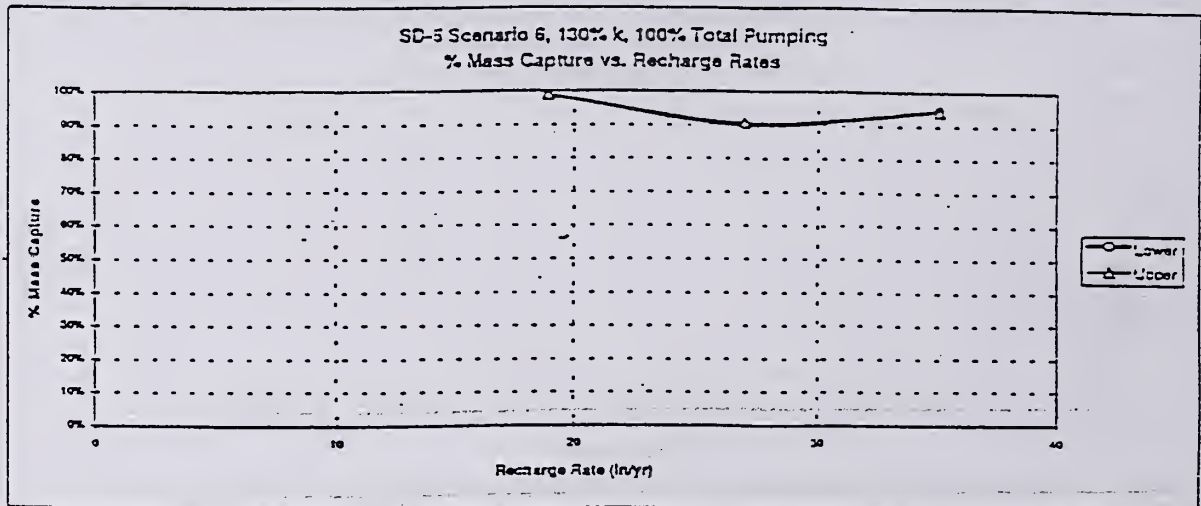
**SD-5 Scenario 6, 100% k, 100% Total Pumping
% Mass Capture vs. Recharge Rates**



**SD-5 Scenario 6, 100% k, 100% Total Pumping
% Volume Capture vs. Recharge Rates**



SD-5 Plume Containment System Performance: 130/#/100											
Run ID	Recharge (In/yr)	SD-5 Plume									
		Total particles	Particles captured	Percent particles captured	Total mass, Lower Bound (micrograms)	Mass captured, Lower Bound (micrograms)	Percent mass captured, Lower Bound	Total mass, Upper Bound (micrograms)	Mass captured, Upper Bound (micrograms)	Percent mass captured, Upper Bound	Percent volume captured
SS	27										
RUN9	18.9	2607	2559	98.16%	8335.2	8232	98.76%	69912	69149	98.91%	98.16%
RUN5	27	2607	2231	85.58%	8335.2	7489	89.85%	69912	63458	90.77%	85.58%
RUN12	35.1	2607	2470	94.74%	8335.2	7879	94.53%	69912	65890	94.25%	94.74%



Environmental Consulting Engineers
MMR SD-5 100/100/70
Model Run Summary
6-12-96

Model: High K Box Model

Description: ECE defined inputs with 100% K field, 100% recharge, and 70% pumping rate.

Recharge = 27 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN2

Extraction Wells = 14 (-248.5 gpm)

- fence: -24.5x2, -14x9, -21, -24.5, -28 gpm

Injection Wells = 14 (248.5 gpm)

- fence: 17.5x4, 21x5, 17.5, 14x4 gpm

Plume Capture, SD-5 Mass:

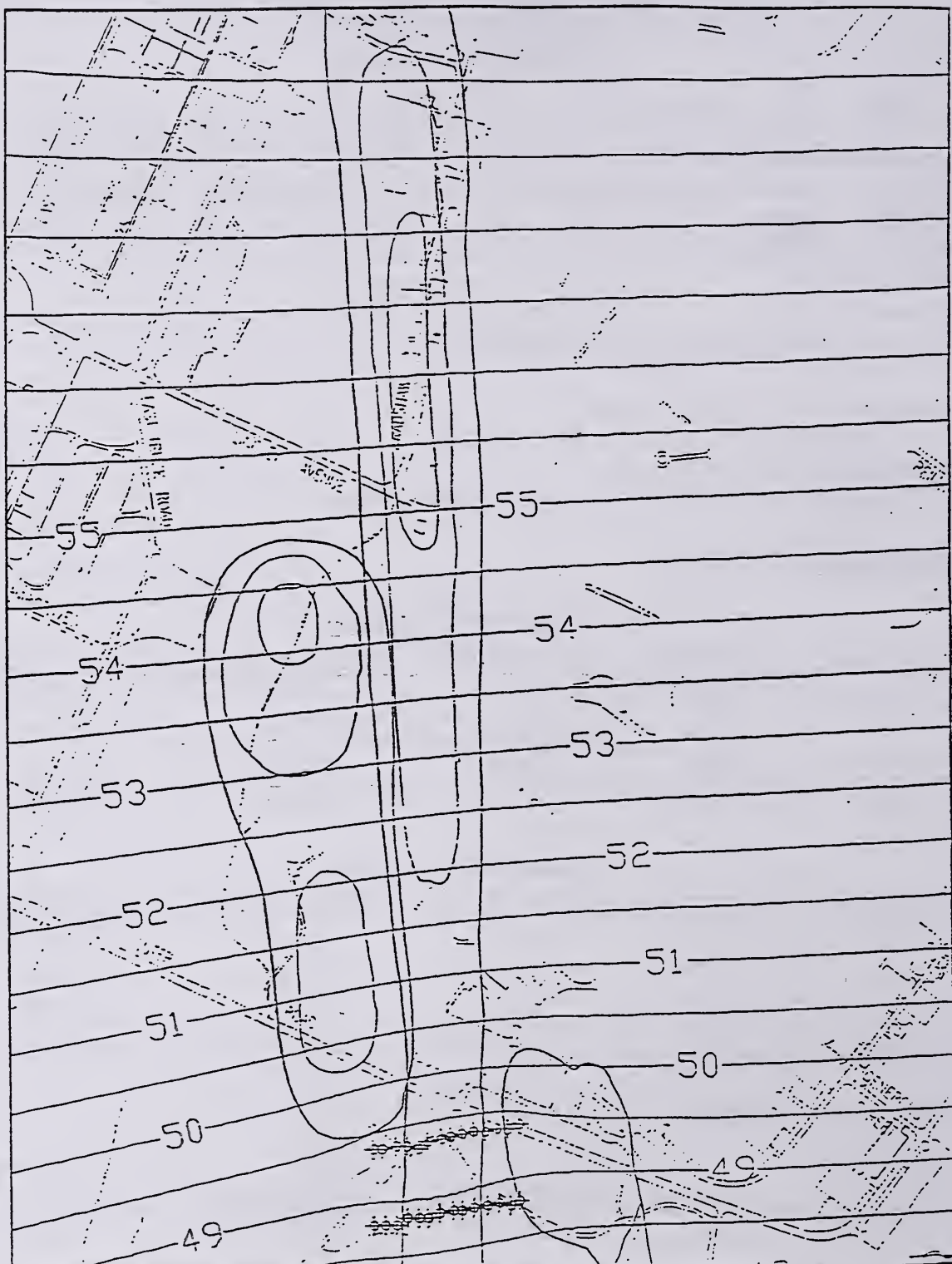
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4032	96.55%
2.4	1033	2479.2	2364	95.35%
1.2	1400	1680	1622.4	96.57%
<i>totals</i>	2607	8335.2	8018.4	96.20%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	40320	96.55%
24	1033	24792	23640	95.35%
2.4	1400	3360	3244.8	96.57%
<i>totals</i>	2607	69912	67204.8	96.13%

Plume Capture Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	21918750	96.09%

* Volume of water per particle using porosity of 35%



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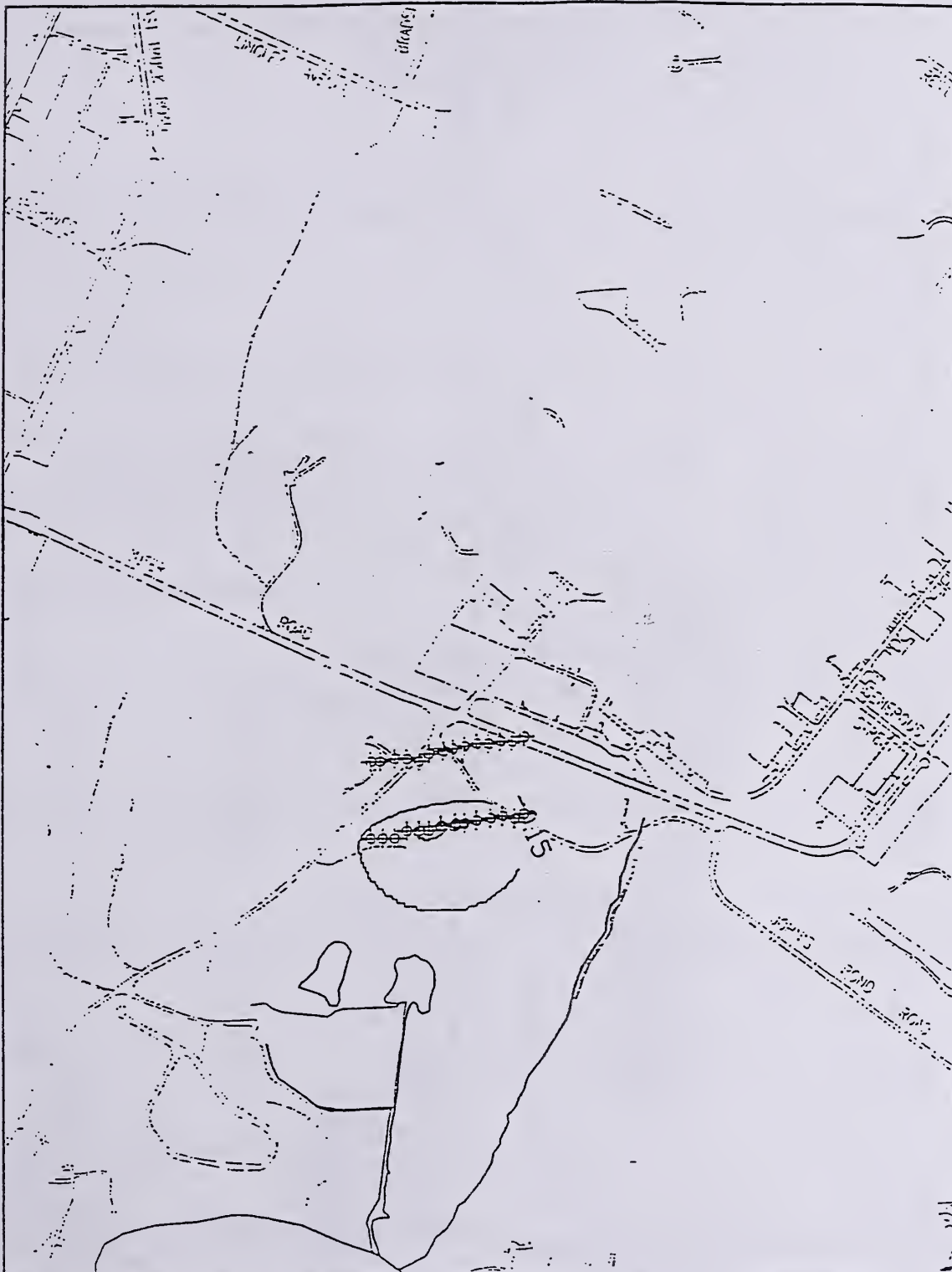
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SD-5 Scenario 6 Run 2 (2±8.5 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD562WT.CWG
Project No.: 07 UMR.01

Drawing No.
S6.2.01



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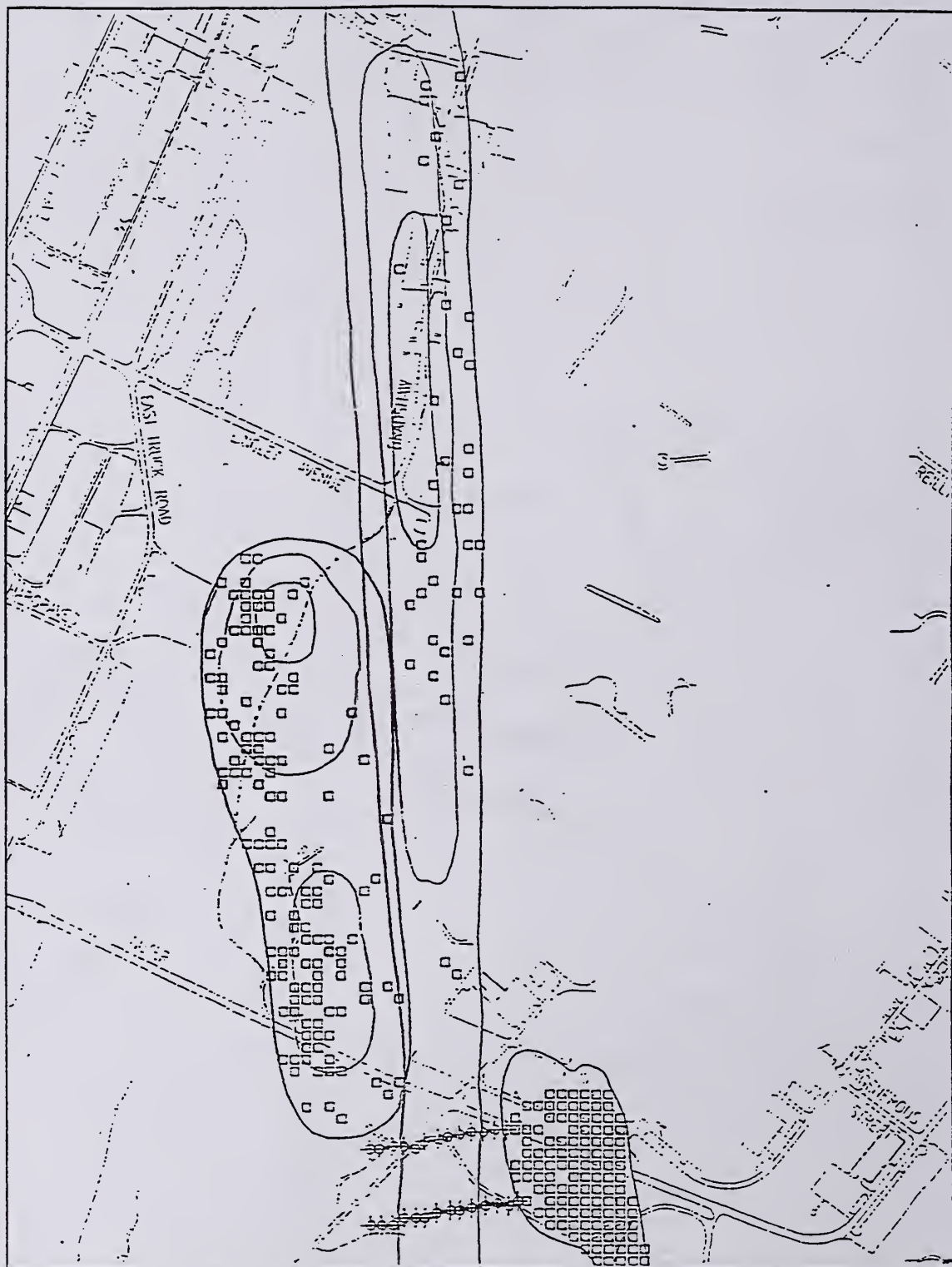
SD-5 Scenario 6 Run 2 (248.5 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 2
Drawn by: BTH
Checked by: MLC
Drawing Name: SD56200.DWG
Project No.: 07 WMR.01

Drawing No.

S6.2.02



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SD-5 Scenario 5 Run 2 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD552P9.DWG
Project No.: OT MMR.01

Drawing No.
S6.2.03

Environmental Consulting Engineers
 MMR SD-5 100/100/130
 Model Run Summary
 6-12-96

Model: High K Box Model

Description: ECE defined inputs with 100% K field, 100% recharge, and 130% pumping rate.

Recharge = 27 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN3

Extraction Wells = 14 (-461.5 gpm)

- fence: -45.5x2, -26x9, -39, -45.5, -52 gpm

Injection Wells = 14 (461.5 gpm)

- fence: 32.5x4, 39x5, 32.5, 26x4 gpm

Plume Capture, SD-5 Mass:

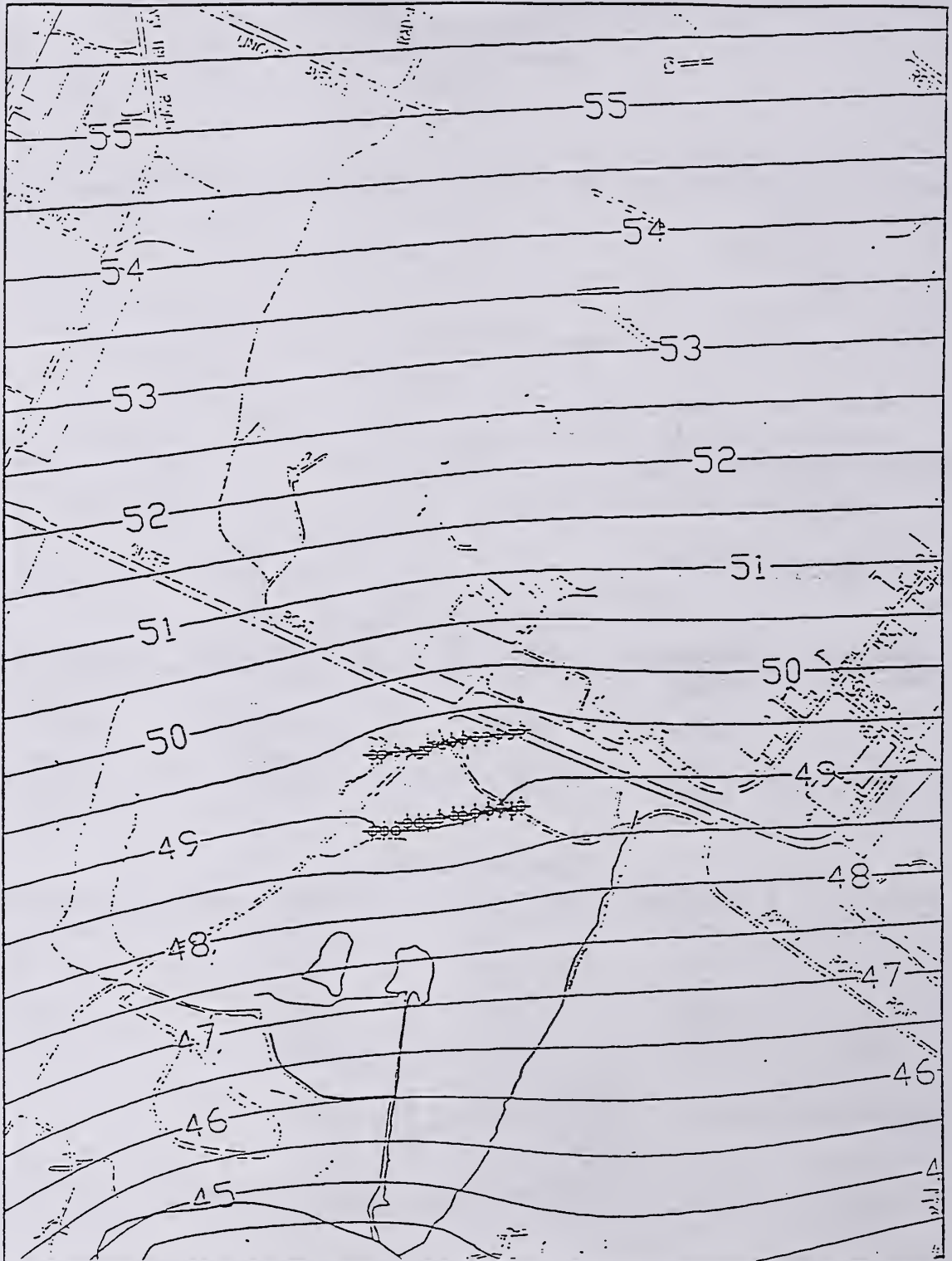
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4128	98.85%
2.4	1033	2479.2	2474.4	99.81%
1.2	1400	1680	1672.8	99.57%
<i>totals</i>	2607	8335.2	8275.2	99.28%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41280	98.85%
24	1033	24792	24744	99.81%
2.4	1400	3360	3345.6	99.57%
<i>totals</i>	2607	69912	69369.6	99.22%

Plume Capture, Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,723,750	99.62%

* Volume of water per particle using porosity of 35%



Environmental Consulting Engineers



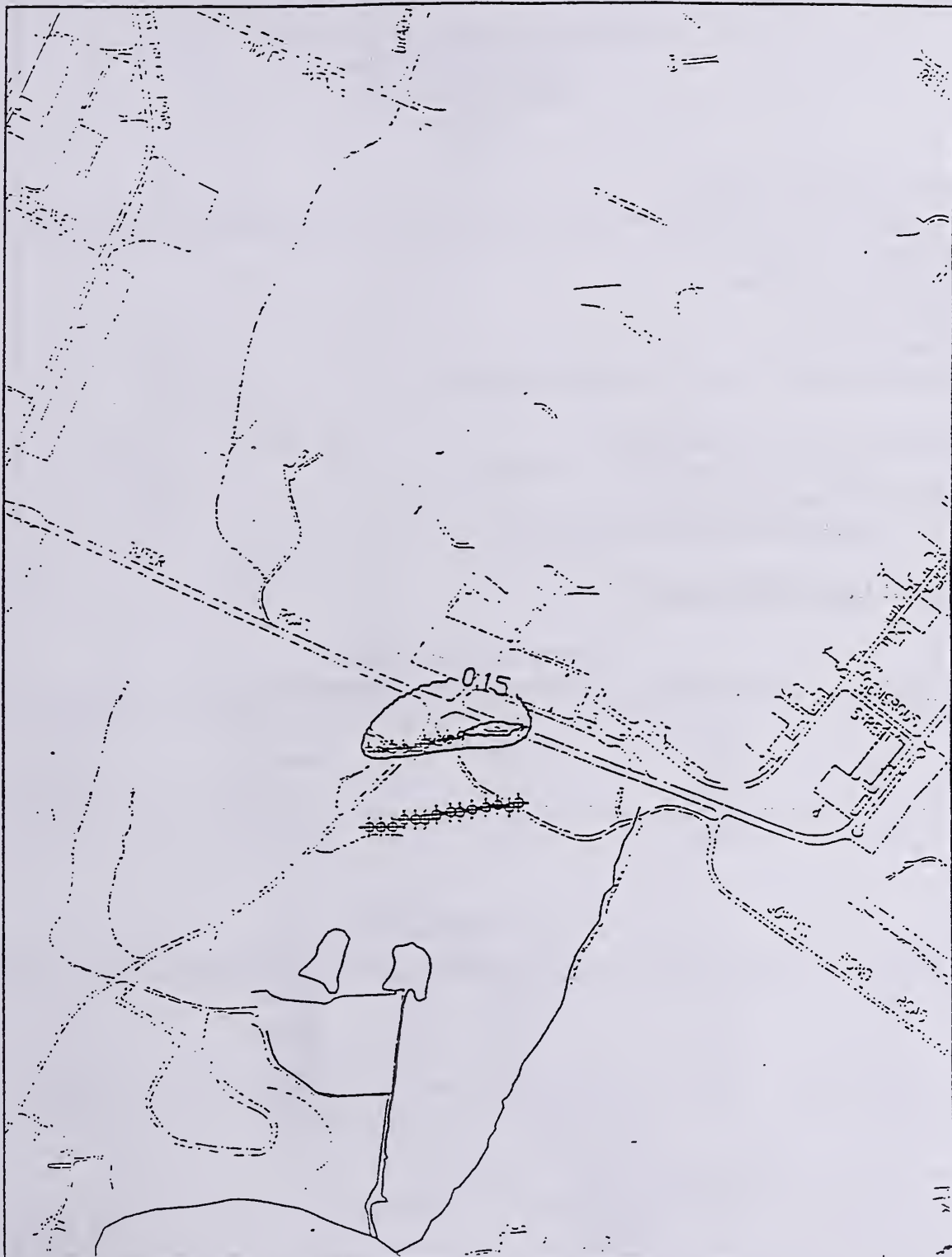
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SD-5 Scenario 6 Run J (+61.5 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLS
Drawing Name: SD55JW.DWG
Project No.: 07 MMR-01

Drawing No.
S6.3.01



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SD-5 Scenario 5 Run 3 (461.5 gpm) Drawdown

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLC
Drawing Name: SD56300.DWG
Project No: 01 MUR.01

Drawing No.

S6.3.02

Environmental Consulting Engineers
MMR SD-5 70/130/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 70% K field, 130% recharge, and 100% pumping rate.

Recharge = 35.1 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN10

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

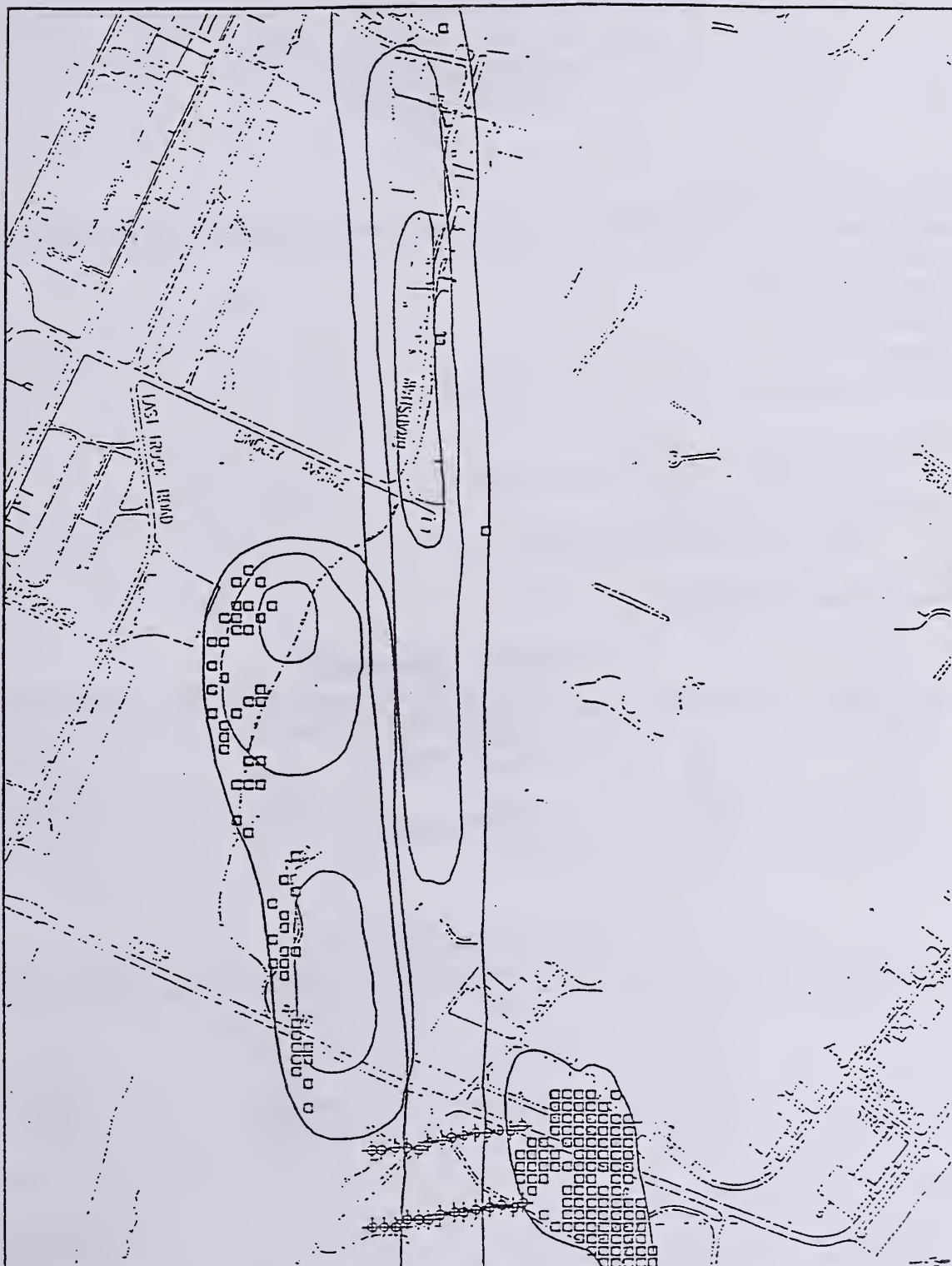
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4032	96.55%
2.4	1033	2479.2	2414.4	97.39%
1.2	1400	1680	1614	96.07%
<i>totals</i>	2607	8335.2	8060.4	96.70%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	40320	96.55%
24	1033	24792	24144	97.39%
2.4	1400	3360	3228	96.07%
<i>totals</i>	2607	69912	67692	96.82%

Plume Capture, by Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,041,250	96.62%

* Volume of water per particle using porosity of 35%



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SD-5 Scenario 6 Run 3 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD53P9.DWG
Project No: 01 MMR-01

Drawing No.
S6.3.03

Environmental Consulting Engineers
MMR SD-5 70/100/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 70% K field, 100% recharge, and 100% pumping rate.

Recharge = 27 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN4

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

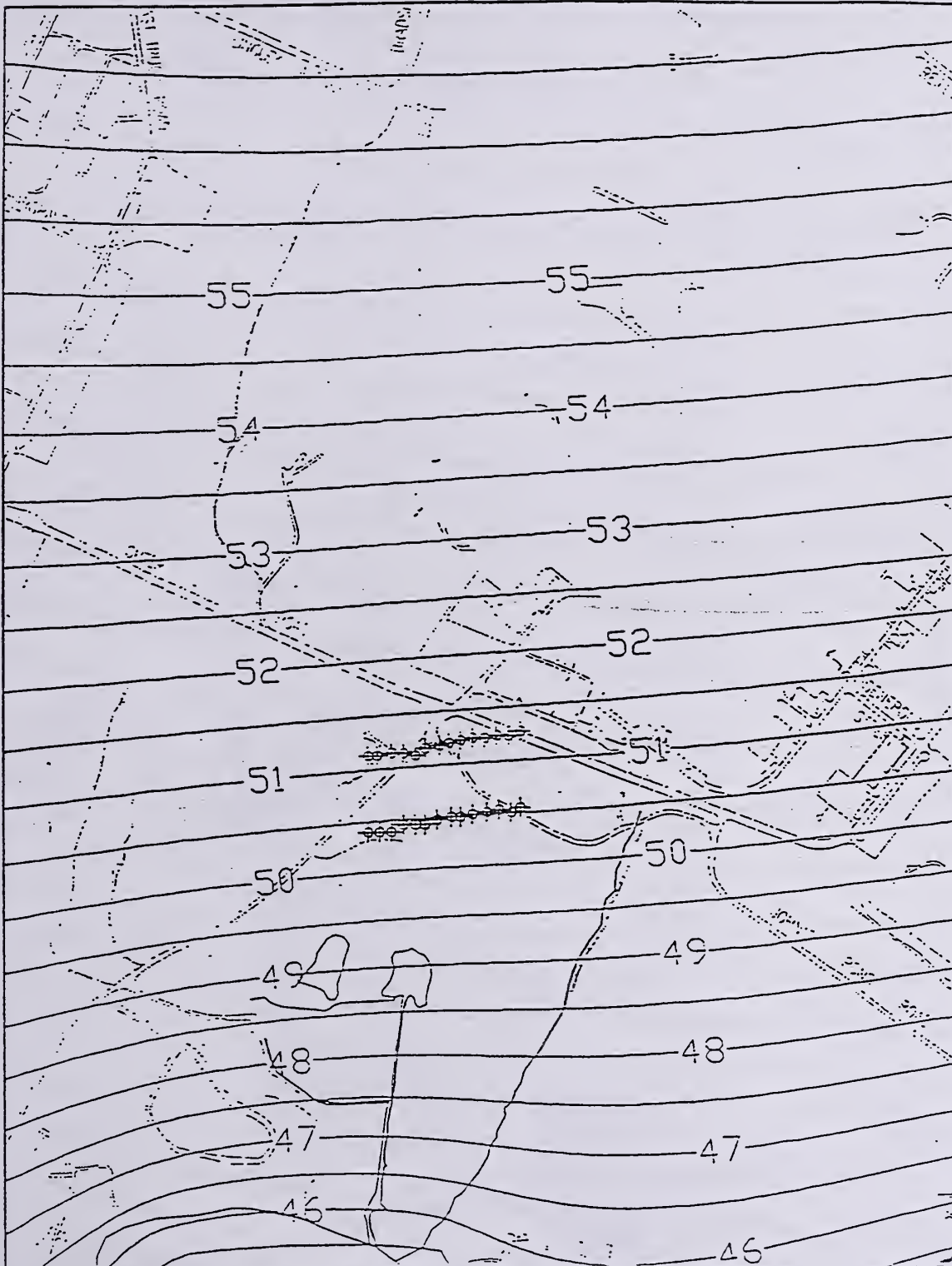
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4056	97.13%
2.4	1033	2479.2	2424	97.77%
1.2	1400	1680	1620	96.43%
<i>totals</i>	2607	8335.2	8100	97.18%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	40560	97.13%
24	1033	24792	24240	97.77%
2.4	1400	3360	3240	96.43%
<i>totals</i>	2607	69912	68040	97.32%

Plume Capture Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,128,750	97.01%

* Volume of water per particle using porosity of 35%



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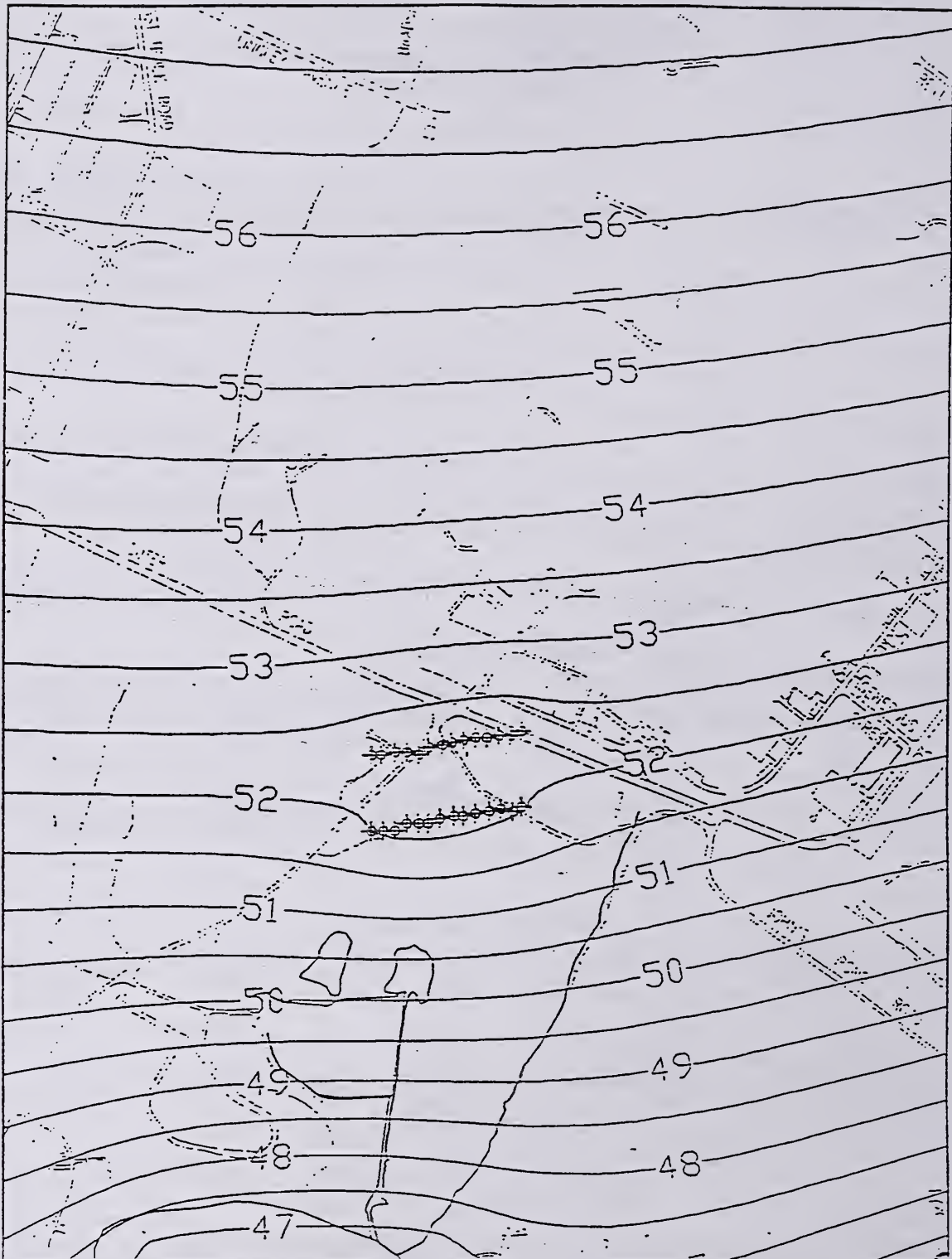
SD-5 Scenario 5 Run 4 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 3
Drawn by: BTH
Checked by: WLC
Drawing Name: SD554SS.DWG
Project No.: 07 MUR.01

Drawing No.

S6.4SS.01



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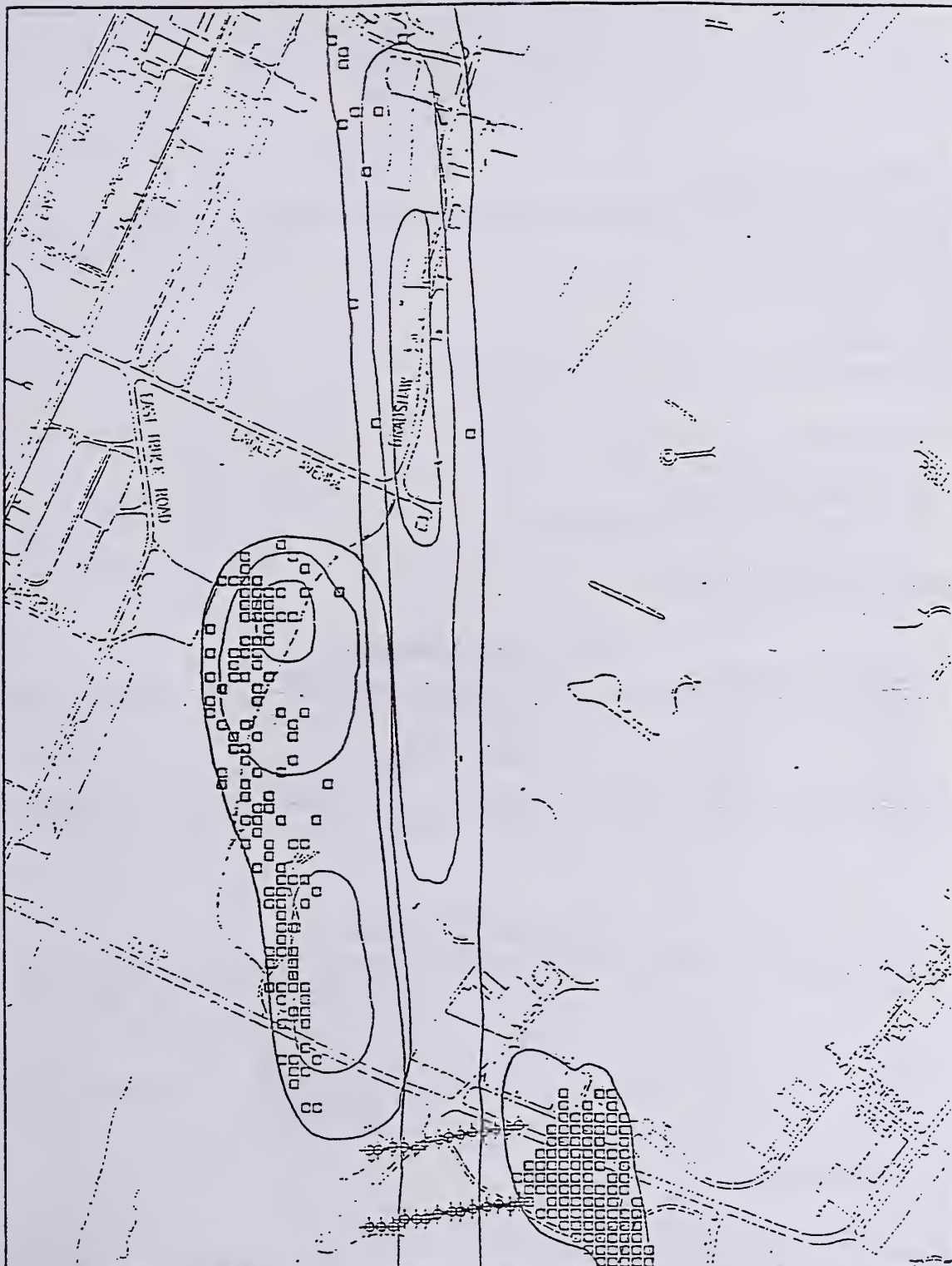
SC-S Scenario 6 Run 4 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: ETH
Checked by: MLC
Drawing Name: S0554WT.DWG
Project No.: CT WMR.01

Drawing No.

S6.4.01



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SD-5 Scenario 5 Run 4 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD554P9.DWG
Project No: 01 WMR.01

Drawing No.

S6.4.02

Environmental Consulting Engineers
MMR SD-5 130/100/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 130% K field, 100% recharge, and 100% pumping rate.

Recharge = 27 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN5

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

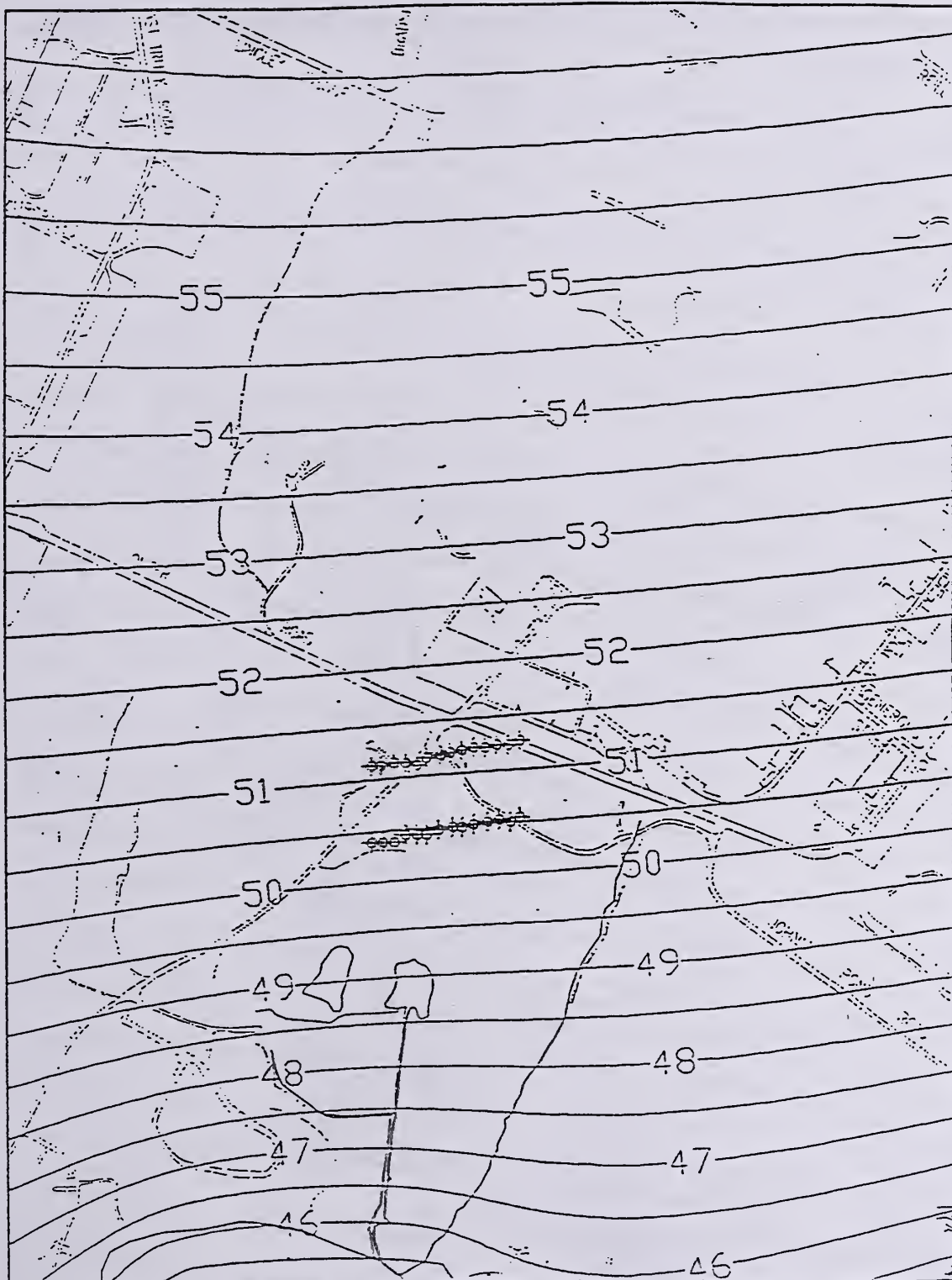
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	3960	94.83%
2.4	1033	2479.2	2100	84.70%
1.2	1400	1680	1429.2	85.07%
<i>totals</i>	2607	8335.2	7489.2	89.85%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	39600	94.83%
24	1033	24792	21000	84.70%
2.4	1400	3360	2858.4	85.07%
<i>totals</i>	2607	69912	63458.4	90.77%

Plume Capture Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	19521250	85.58%

* Volume of water per particle using porosity of 35%



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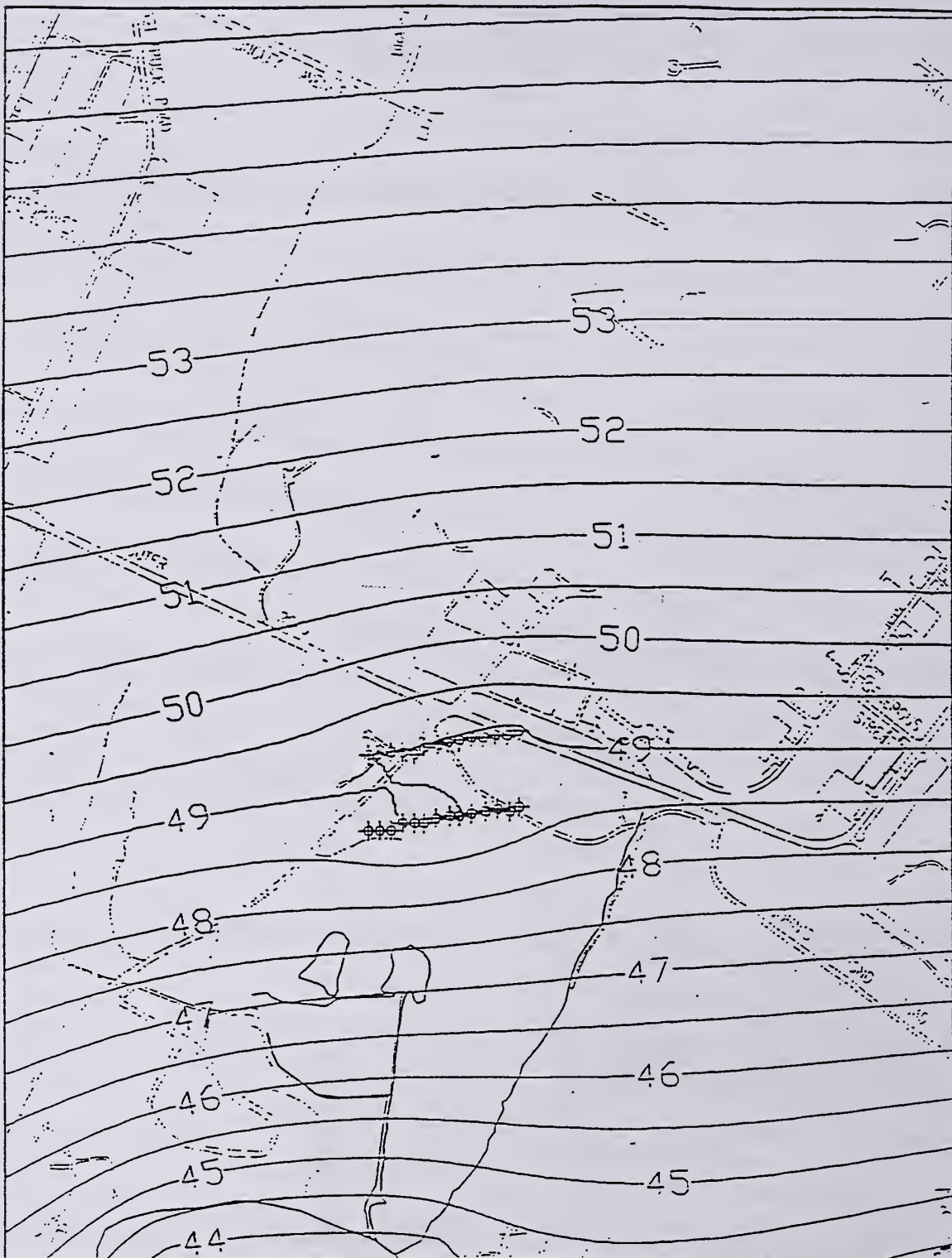
SD-5 Scenario 5 Run 5 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: BTH
 Checked by: WLC
 Drawing Name: SD55SS.DWG
 Project No: 07 WMR.01

Drawing No.

S6.5SS.01



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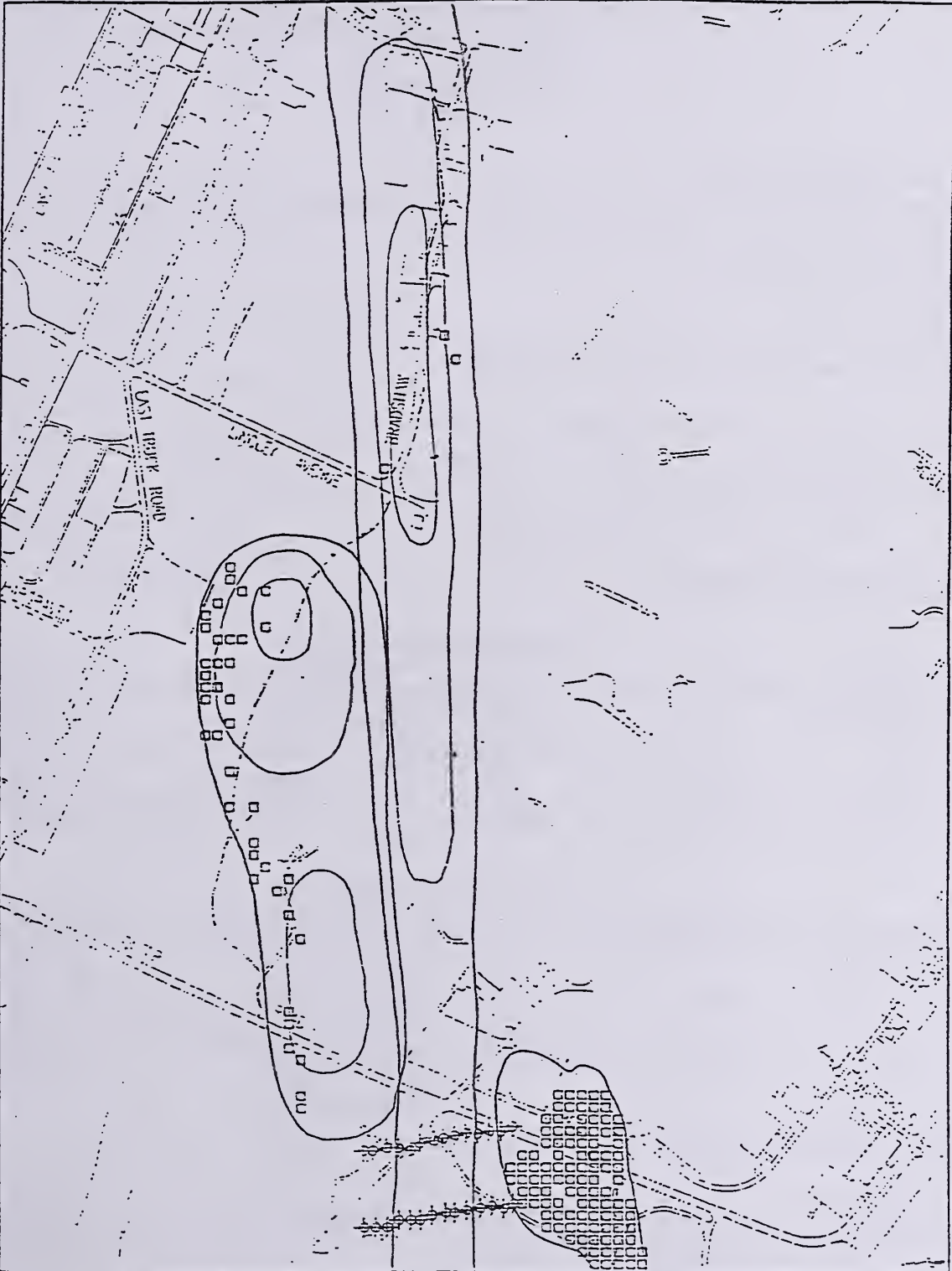
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Fax: (423) 691-3611

SD-3 Scenario 6 Run 6 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD566WT.DWG
Project No.: QT WMR, G1

Drawing No.
S6.6.01



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SD-3 Scenario 6 Run 6 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. C
Drawn by: MLC
Checked by:
Drawing Name: SD356P9.DWG
Project No: OT MMR 01

Drawing No.

S6.5.02

Environmental Consulting Engineers
MMR SD-5 70/70/70
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 70% K field, 70% recharge, and 70% pumping rate.

Recharge = 18.9 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN7

Extraction Wells = 14 (-248.5 gpm)

- fence: -24.5x2, -14x9, -21, -24.5, -28 gpm

Injection Wells = 14 (248.5 gpm)

- fence: 17.5x4, 21x5, 17.5, 14x4 gpm

Plume Capture, SD-5 Mass:

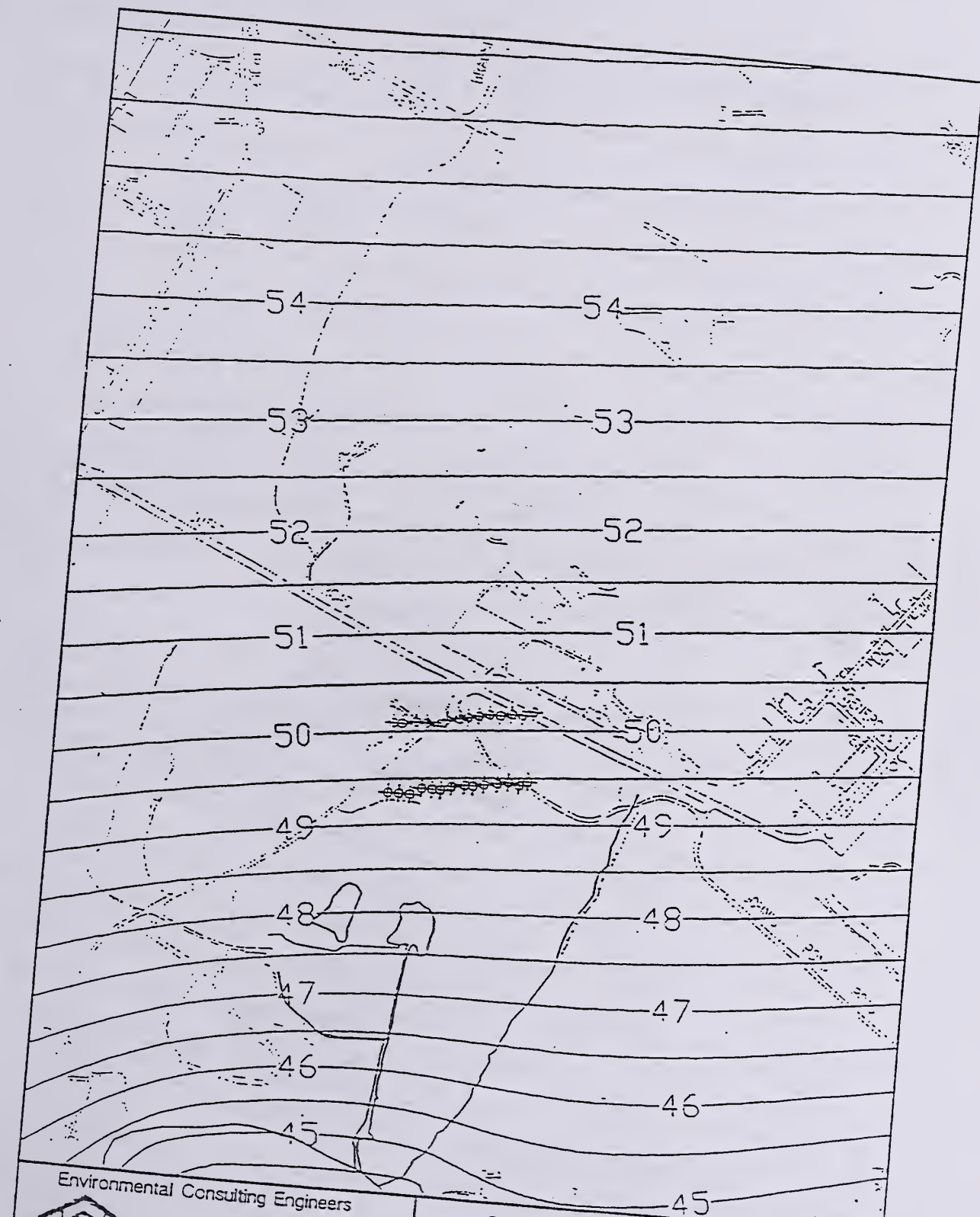
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4152	99.43%
2.4	1033	2479.2	2464.8	99.42%
1.2	1400	1680	1669.2	99.36%
<i>totals</i>	2607	8335.2	8286	99.41%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41520	99.43%
24	1033	24792	24648	99.42%
2.4	1400	3360	3338.4	99.36%
<i>totals</i>	2607	69912	69506.4	99.42%

Plume Capture, by Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22671250	99.39%

* Volume of water per particle using porosity of 35%



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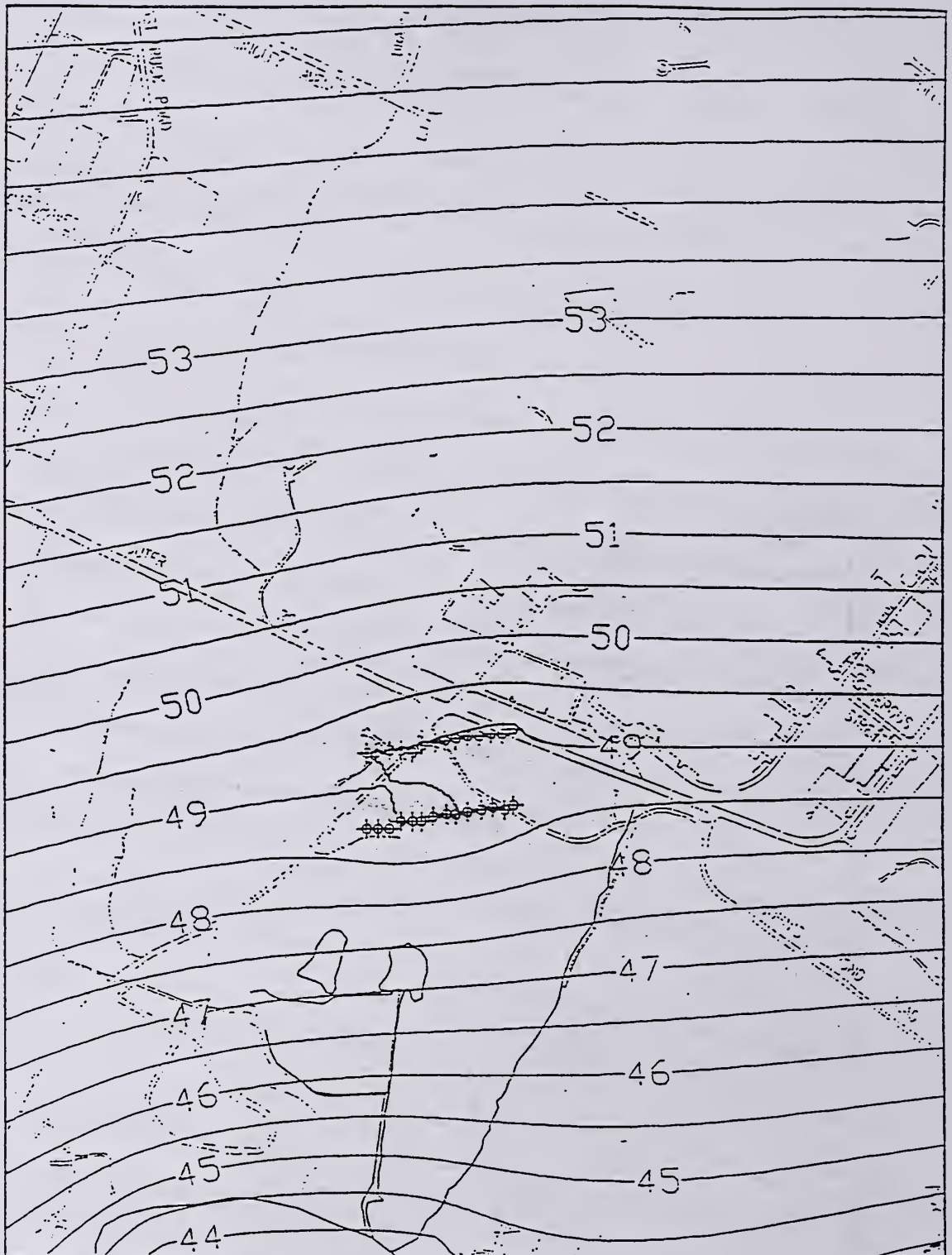
SD-5 Scenario 6 Run 6 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD566SS.DWG
Project No: 01 UMR.01

Drawing No.

S6.6SS.01



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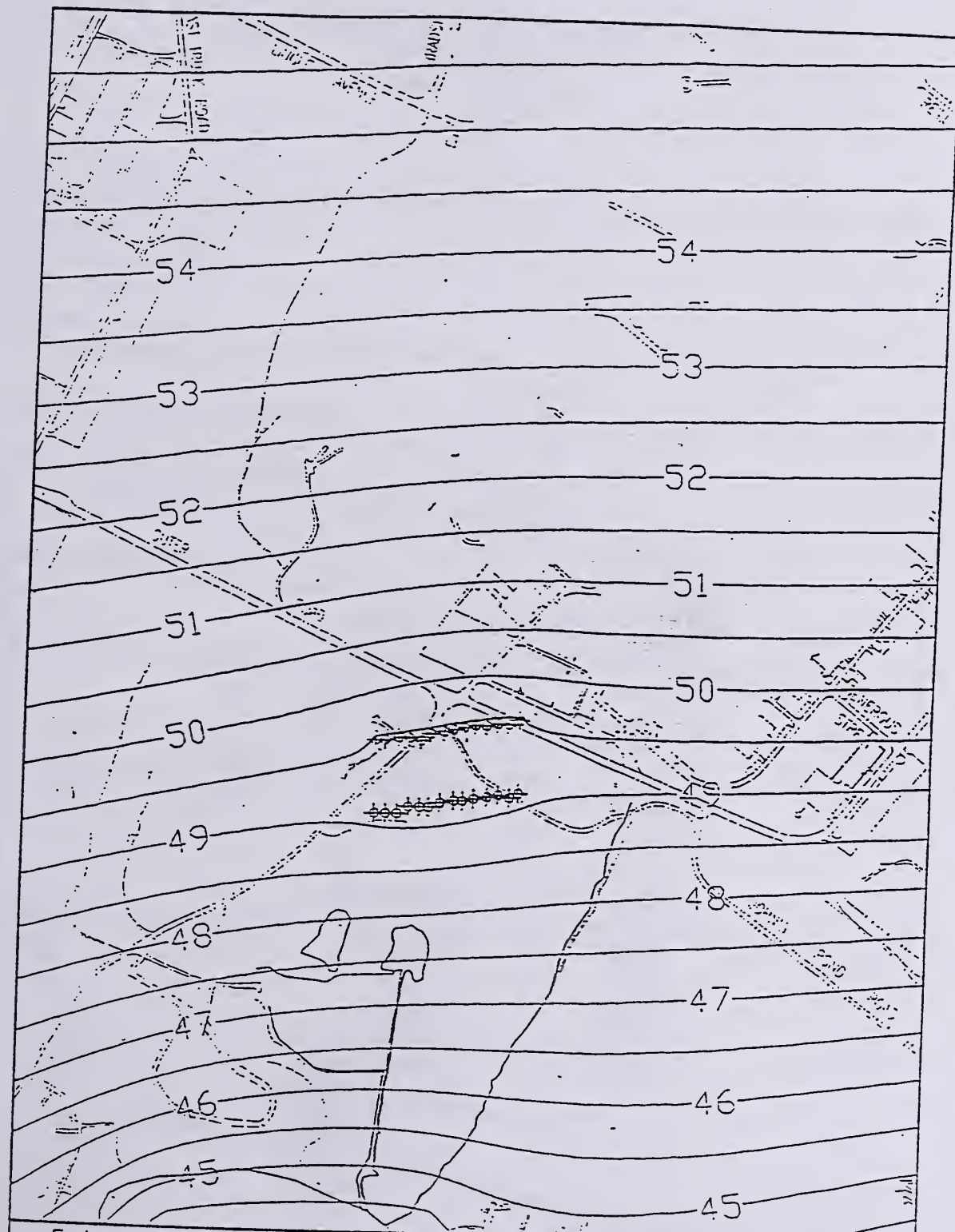
SD-5 Scenario 5 Run 6 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD565WT.DWG
Project No.: OT WMR.01

Drawing No.

S6.6.01



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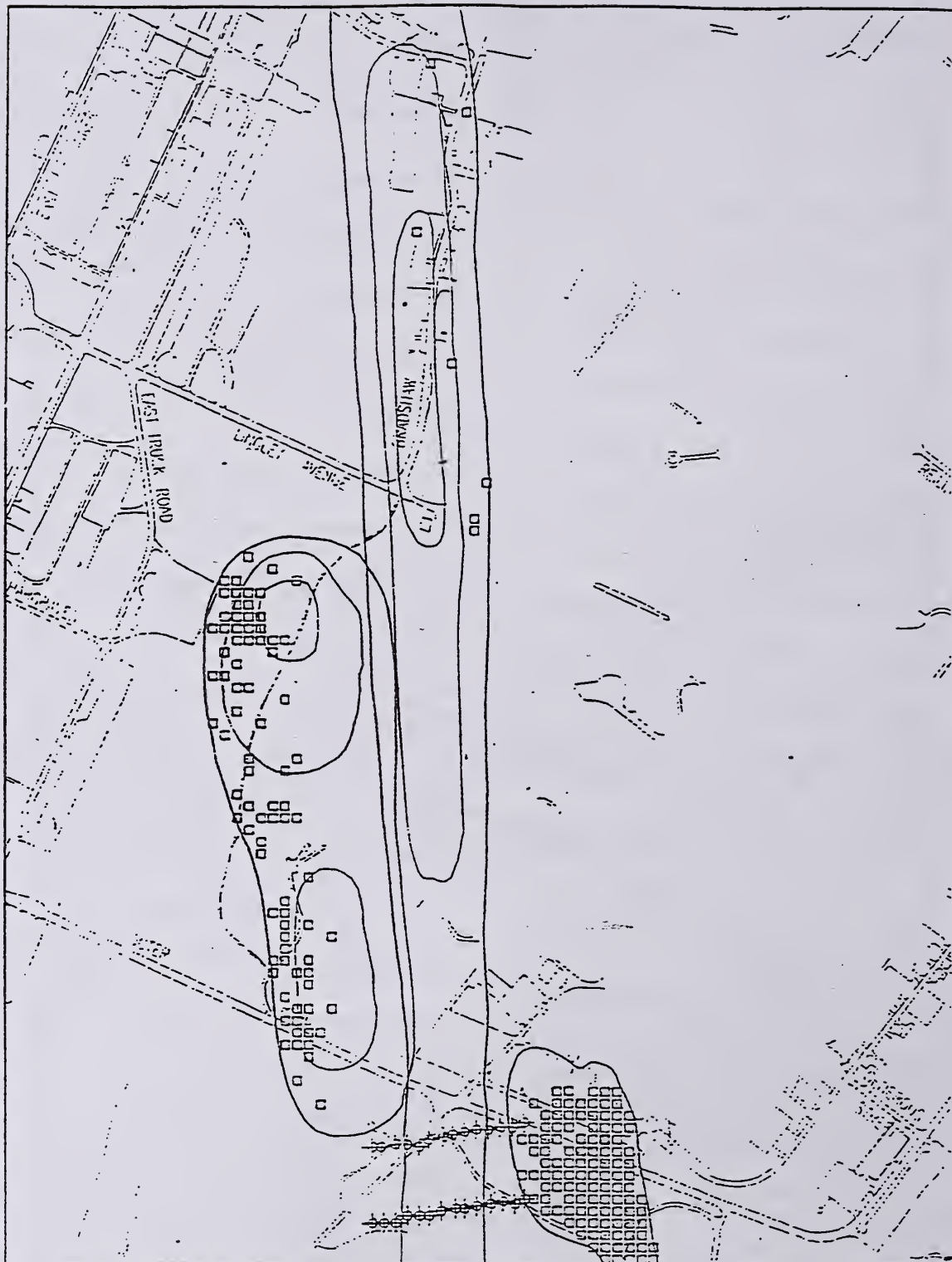
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SD-5 Scenario 6 Run 7 (248.5 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLC
Drawing Name: SD557WT.DWG
Project No.: 07 MMR-01

Drawing No.
S6.7.01



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SD-5 Scenario 6 Run 7 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD55779.DWG
Project No.: CT VMR.01

Drawing No.

S6.7.02

Environmental Consulting Engineers
MMR SD-5 100/70/100
Model Run Summary
6-12-96

Model: High K Box Model

Description: ECE defined inputs with 100% K field, 70% recharge, and 100% pumping rate.

Recharge = 18.9 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN8

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

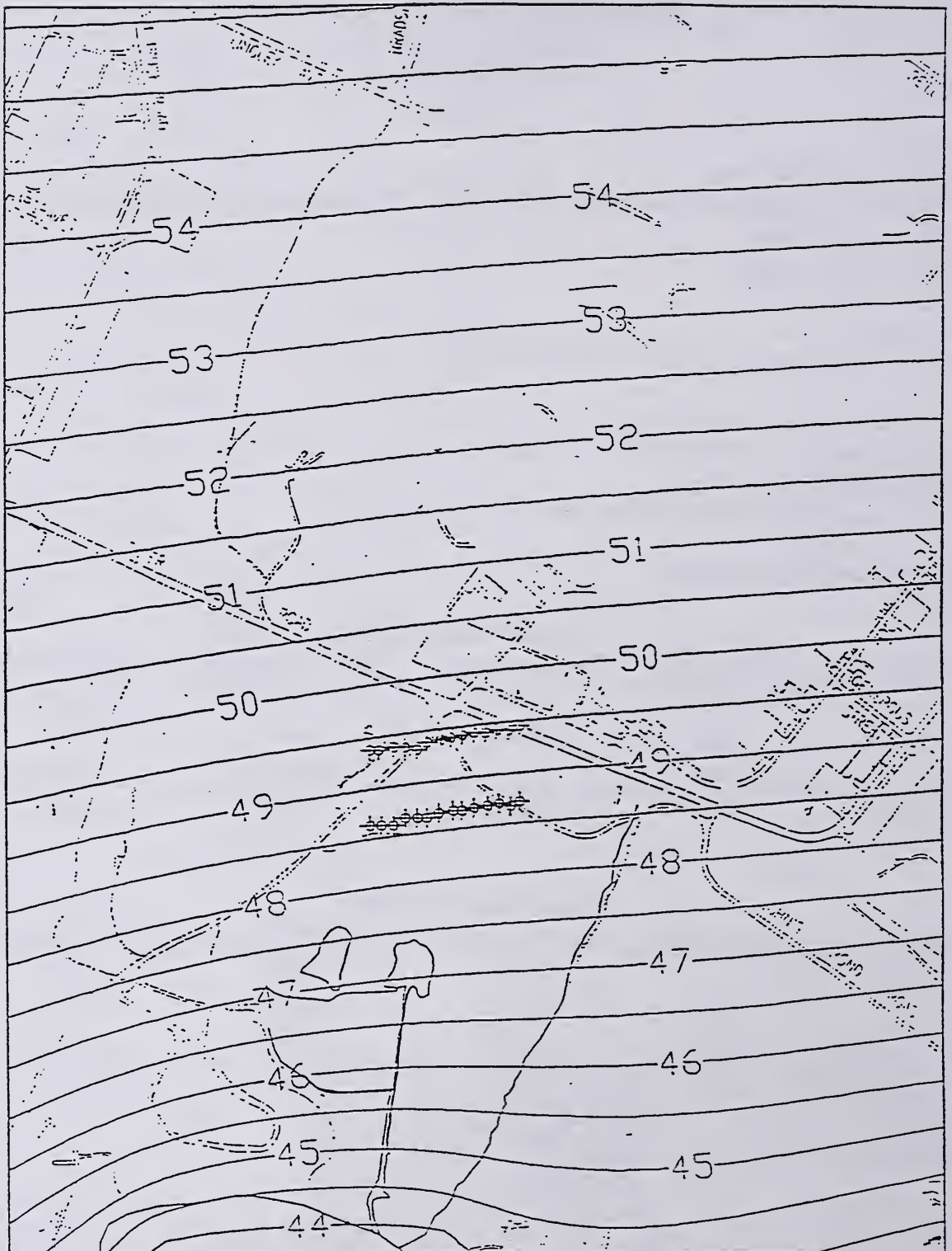
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4008	95.98%
2.4	1033	2479.2	2424	97.77%
1.2	1400	1680	1641.6	97.71%
<i>totals</i>	2607	8335.2	8073.6	96.86%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	40080	95.98%
24	1033	24792	24240	97.97%
2.4	1400	3360	3283.2	97.71%
<i>totals</i>	2607	69912	67603.2	96.70%

Plume Capture Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,268,750	97.62%

* Volume of water per particle using porosity of 35%



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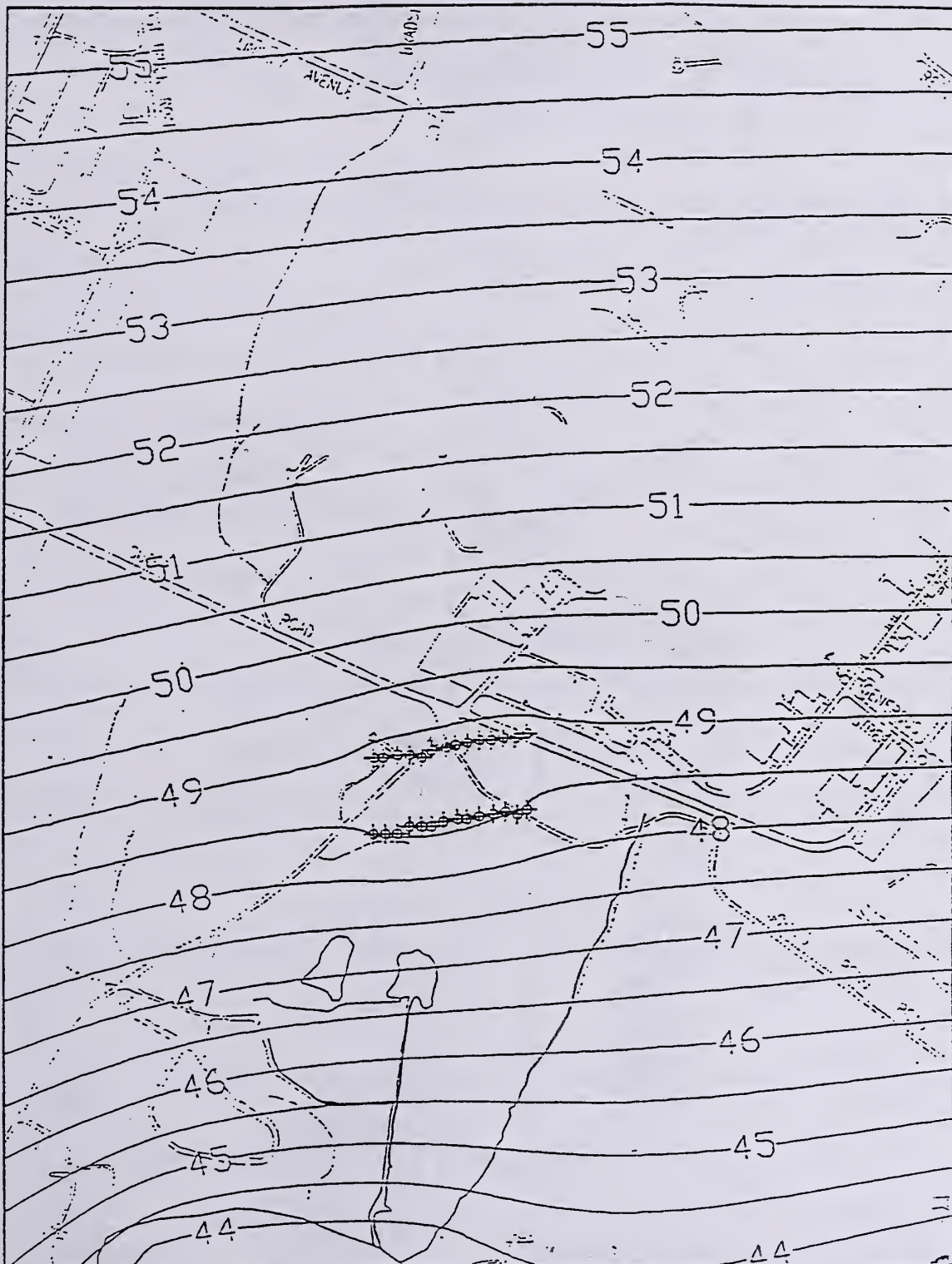
SD-5 Scenario 6 Run 8 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD5SS3.DWG
Project No: OT MMR.01

Drawing No.

S6.8SS.01



Environmental Consulting Engineers



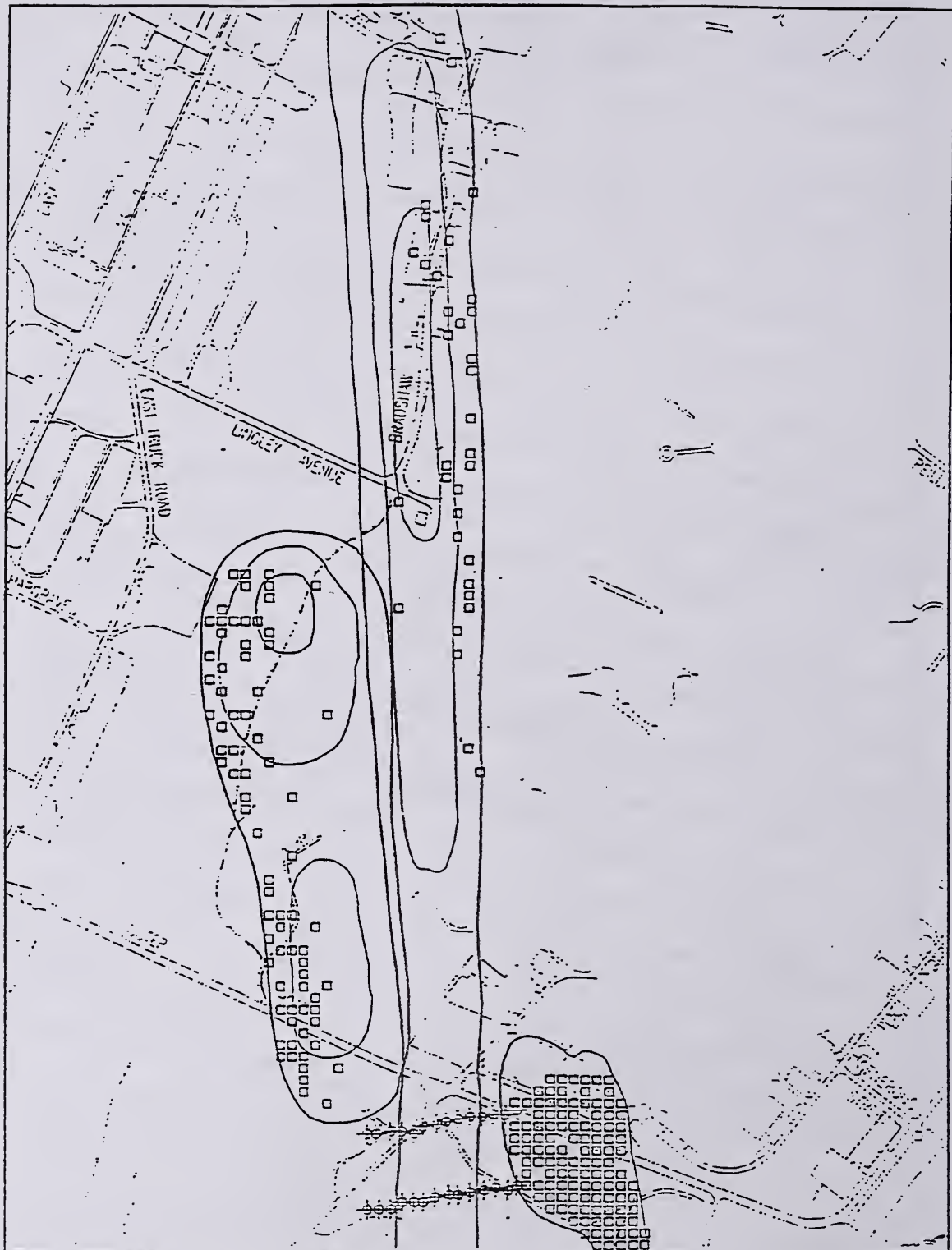
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SD-5 Scenario 6 Run 8 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version: Not Rev. 0
Drawn by: BJA
Checked by: WLC
Drawing Name: SD558WT.DWG
Project No: 07 MMR-01

Drawing No.
S6.8.01



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MMR SC-5 Scenario 6 Run 8 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0

Drawn by: MLC

Checked by:

Drawing Name: SC562P8.DWG

Project No: 07 MMR.01

Drawing No.

S6.8. 02

Environmental Consulting Engineers
MMR SD-5 130/70/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 130% K field, 70% recharge, and 100% pumping rate.

Recharge = 18.9 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN9

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

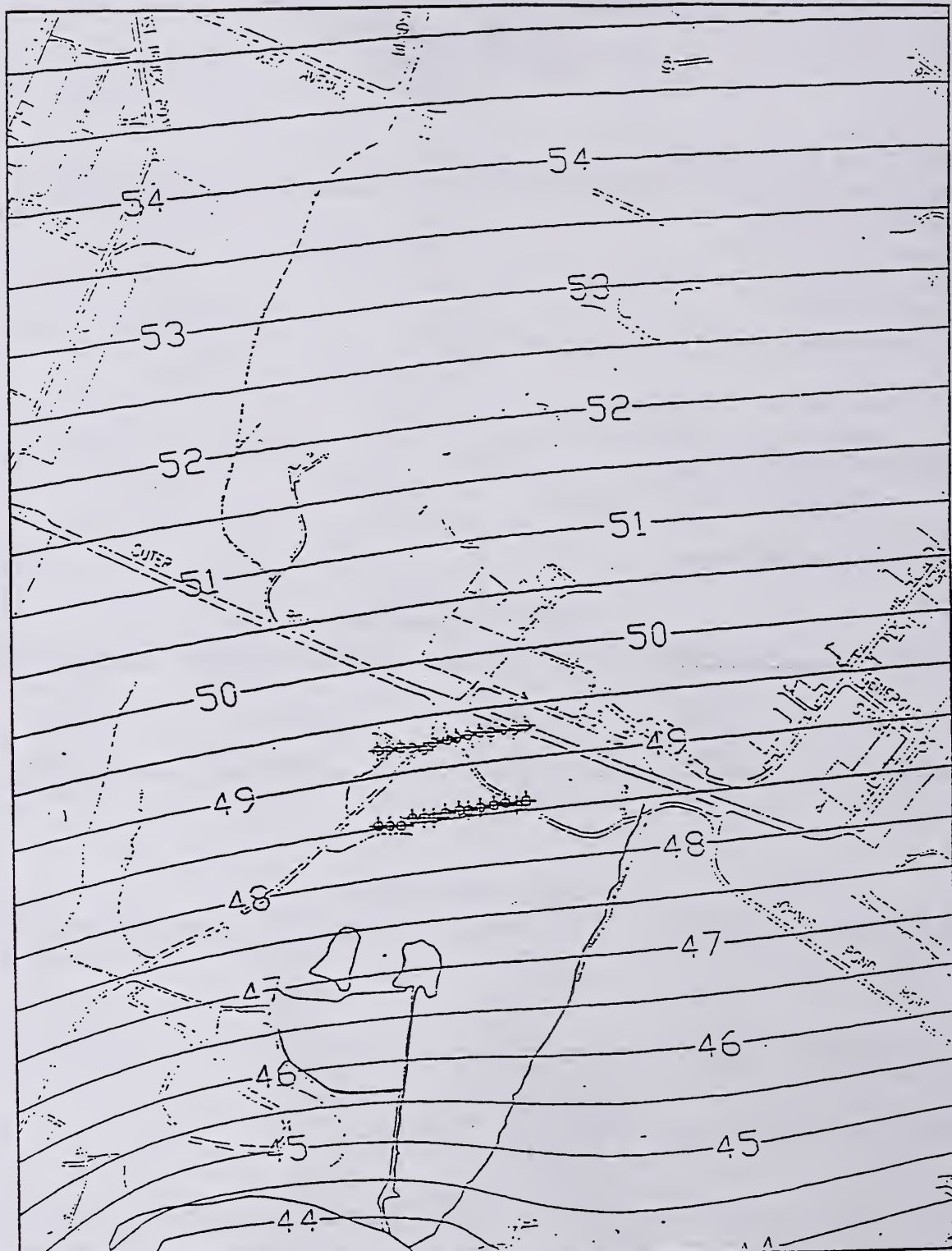
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4152	99.43%
2.4	1033	2479.2	2433.6	98.16%
1.2	1400	1680	1646.4	98.00%
<i>totals</i>	2607	8335.2	8232	98.76%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41520	99.43%
24	1033	24792	24336	98.16%
2.4	1400	3360	3292.8	98.00%
<i>totals</i>	2607	69912	69148.8	98.91%

Plume Capture, by Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,391,250	98.16%

* Volume of water per particle using porosity of 35%



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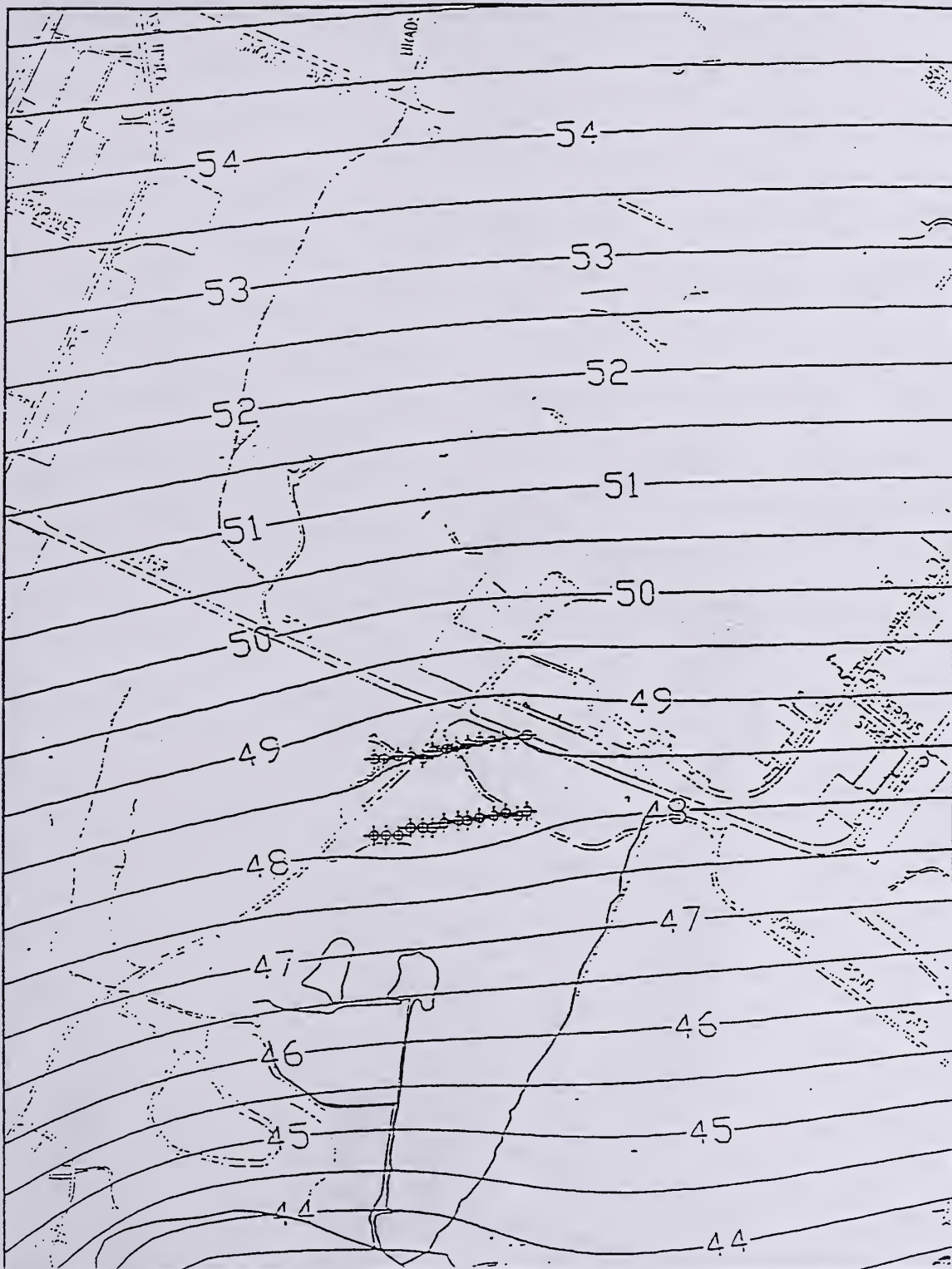
S0-5 Scenario 6 Run 9 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: S05S9SS.DWG
Project No: 07 MMR.D1

Drawing No.

S6.9SS.01



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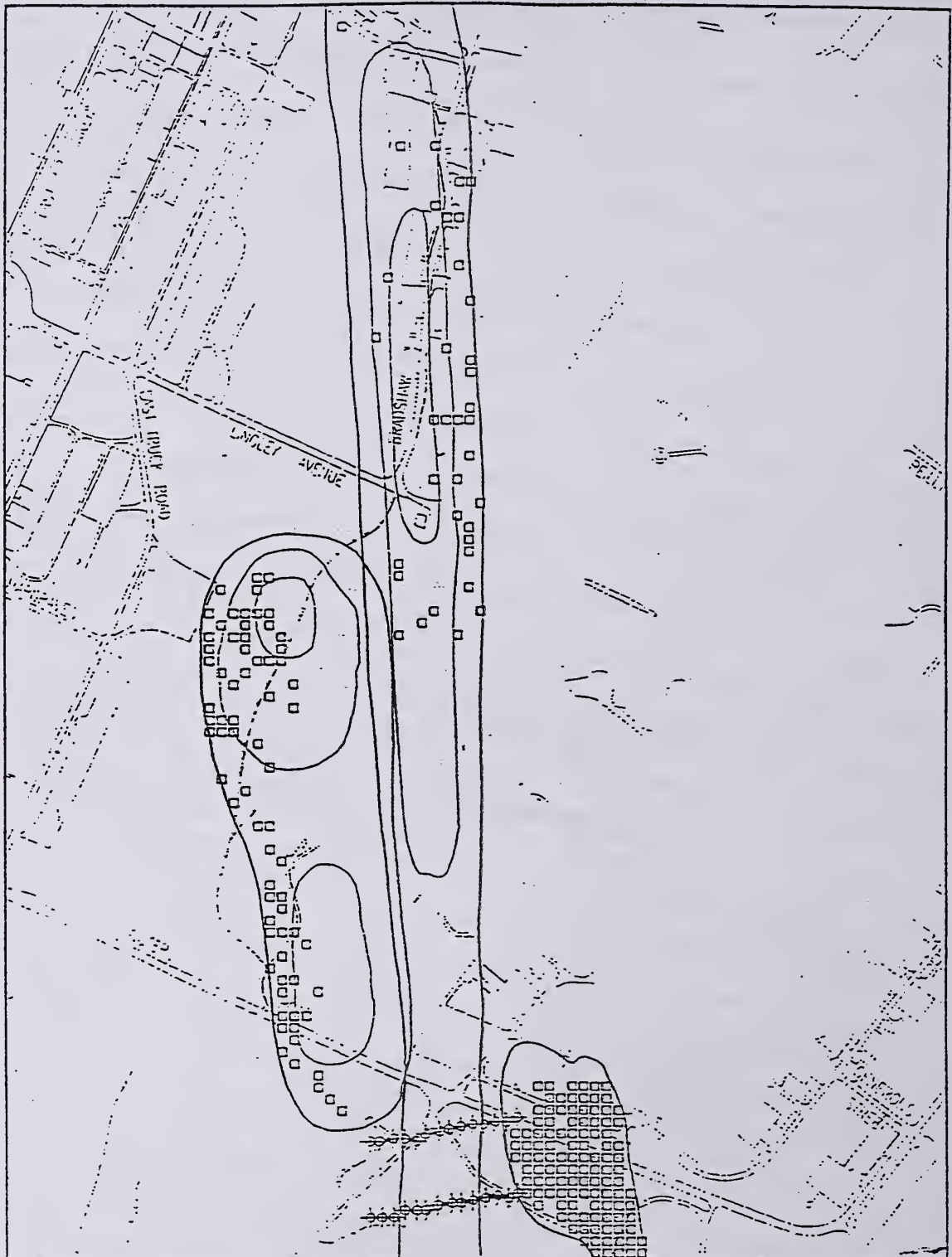
SD-5 Scenario 6 Run 9 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 3
Drawn by: BTH
Checked by: VLS
Drawing Name: SD559W.DWG
Project No.: GT MMR-21

Drawing No.

S6.9.01



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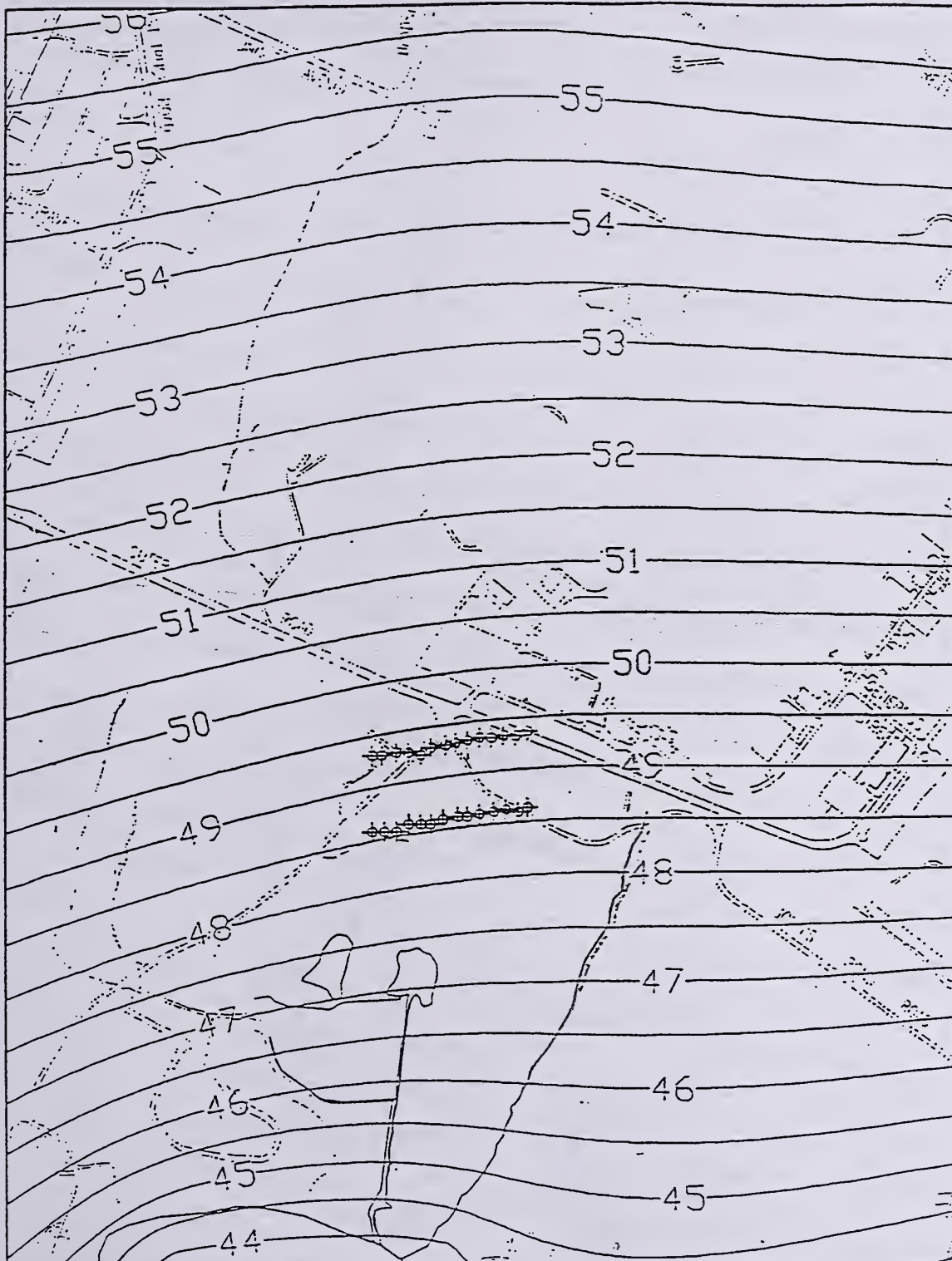
MMR SD-S Scenario 5 Run 9 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: WLC
Checked by:
Drawing Name: SD559PB.DWG
Project No.: 07 MMR.01

Drawing No.

S6.9.02



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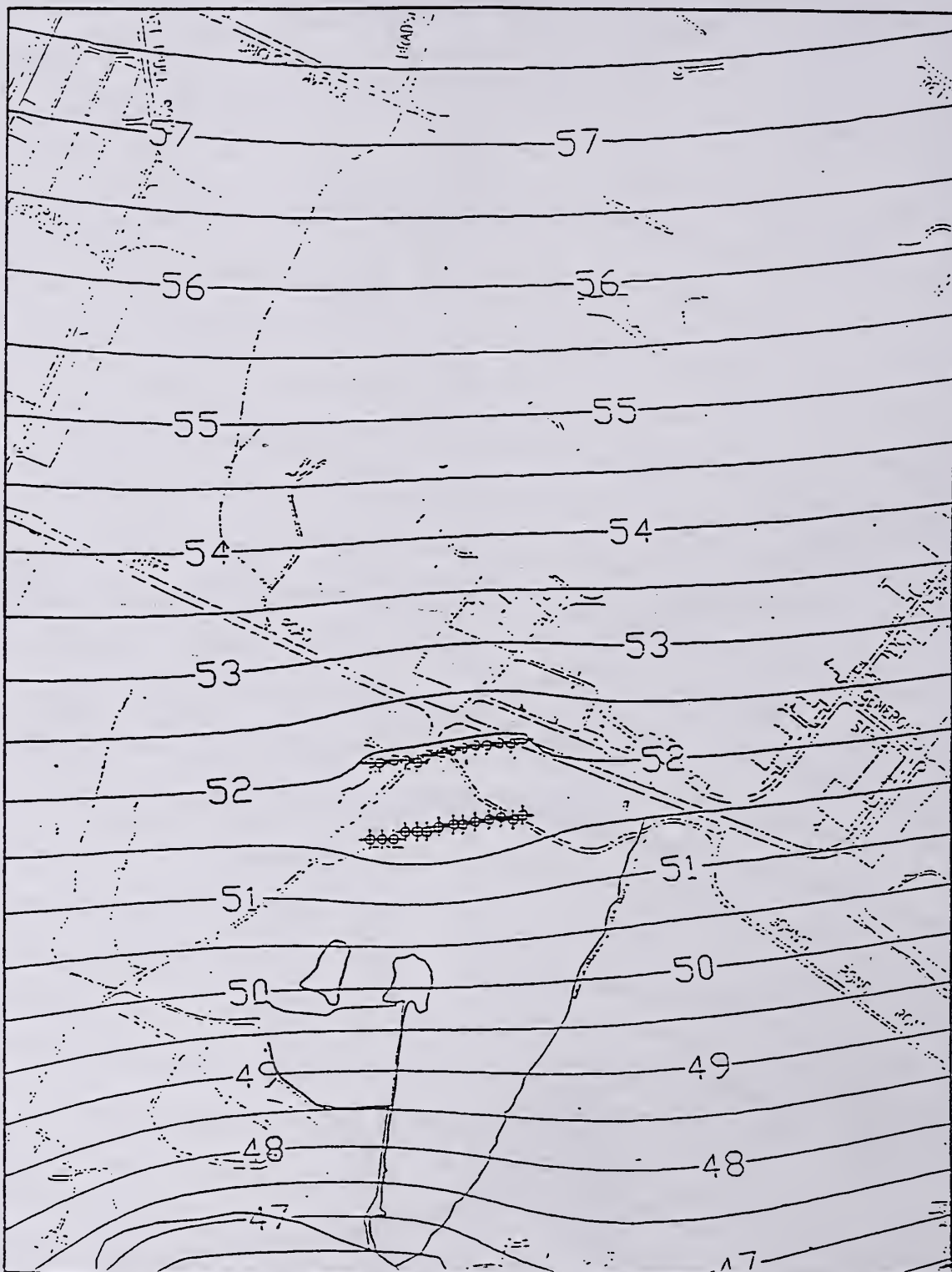
SD-5 Scenario 6 Run 10 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD5S10SS.DWG
Project No.: 07 MMR.01

Drawing No.

S6.10SS.01



Environmental Consulting Engineers



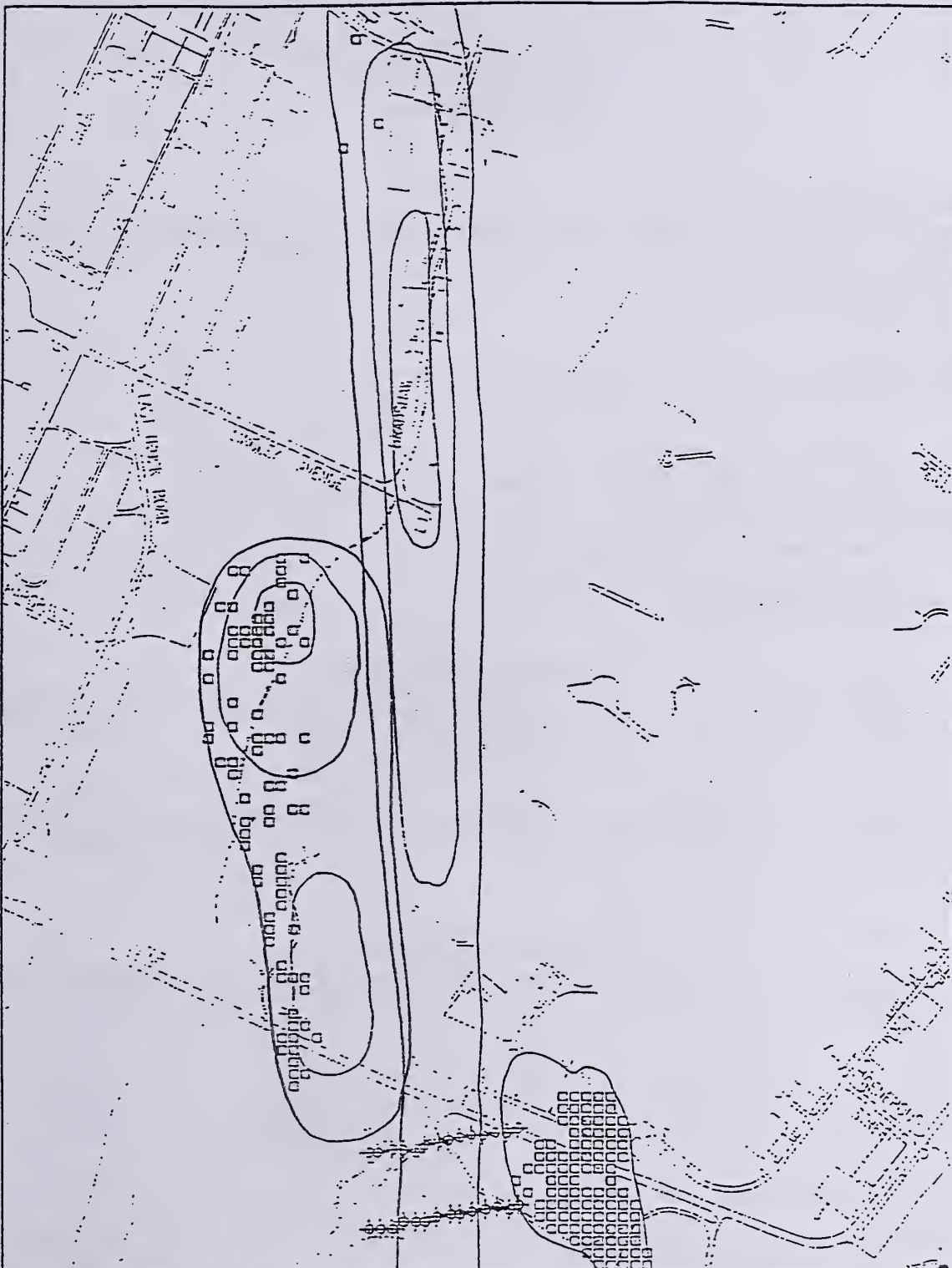
P.O. Box 22668
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 Phone: (423) 551-6668
 Fax: (423) 551-6671

SD-5 Scenario 6 Run 10 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
 Drawn by: BTH
 Checked by: MLC
 Drawing Name: SD5610WT.DWG
 Project No: OT WMR.01

Drawing No.
 S6.10.01



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MMR SD-5 Scenario 5 Run 10 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD551CP9.DWG
Project No: QT MMR_01

Drawing No.

S6.10.02

Environmental Consulting Engineers
MMR SD-5 100/130/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 100% K field, 130% recharge, and 100% pumping rate.

Recharge = 35.1 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN11

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

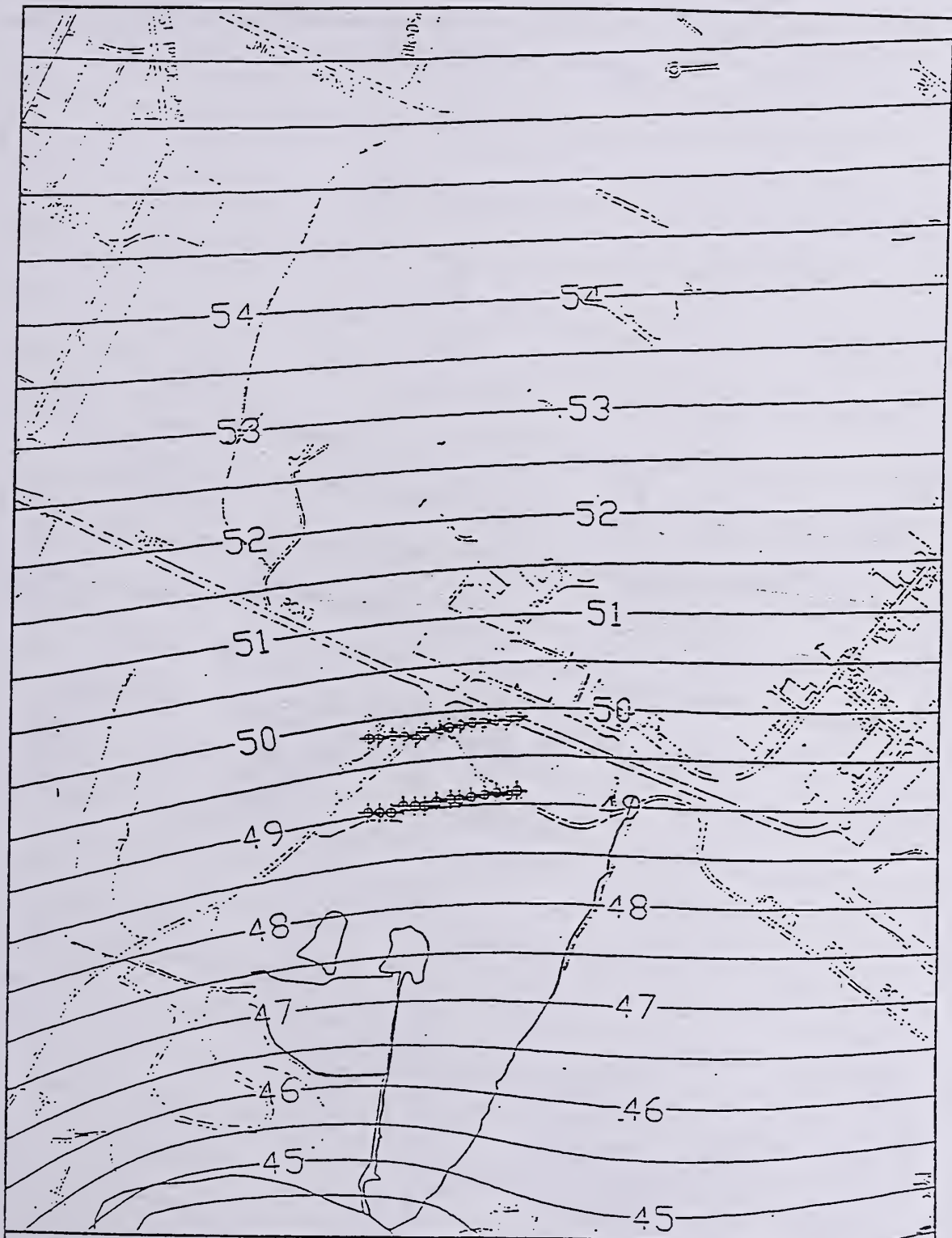
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4128	98.85%
2.4	1033	2479.2	2440.8	98.45%
1.2	1400	1680	1648.8	98.14%
<i>totals</i>	2607	8335.2	8217.6	98.59%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41280	98.85%
24	1033	24792	24408	98.45%
2.4	1400	3360	3297.6	98.14%
<i>totals</i>	2607	69912	68985.6	98.67%

Plume Capture Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22,426,250	98.31%

* Volume of water per particle using porosity of 35%



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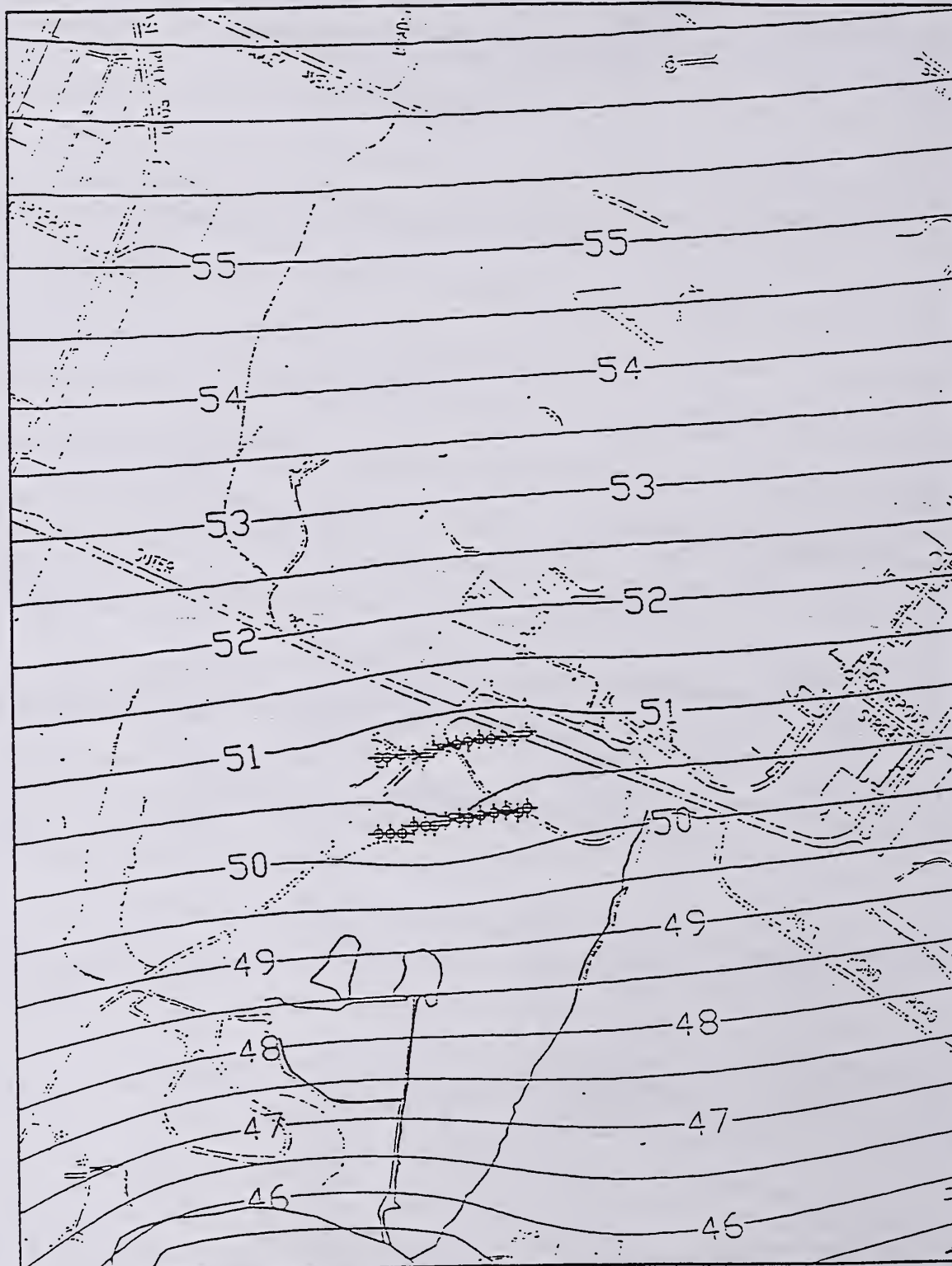
SD-5 Scenario 6 Run 11 SS Water Table

Massachusetts Military Reservation

Drawing Version No. Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD511SS.DWG
Project No.: CT UMR.01

Drawing No.

S6.11SS.01



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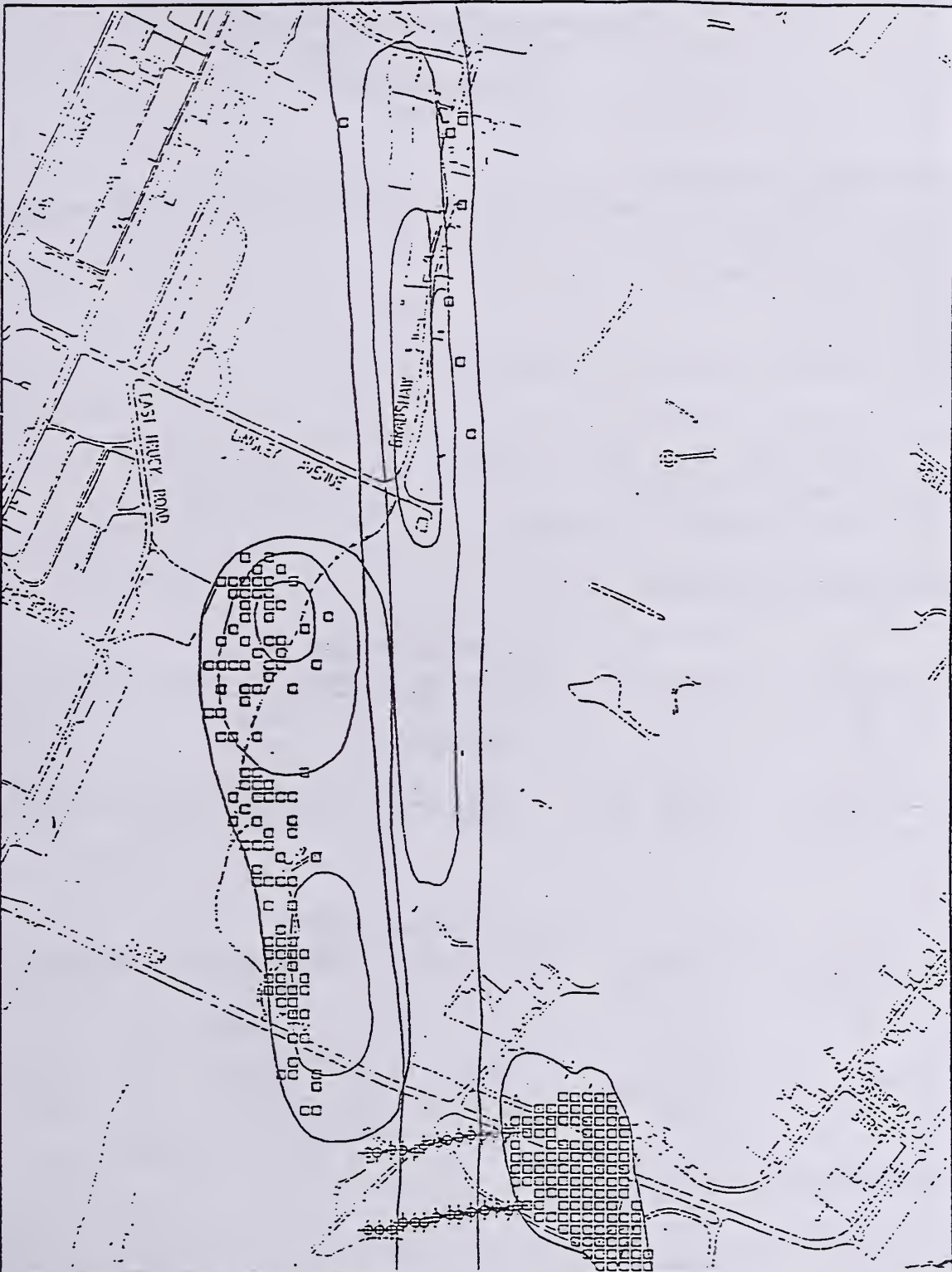
SD-5 Scenario 6 Run 11 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLG
Drawing Name: SD511WT.DWG
Project No.: 07 VMR.01

Drawing No.

S6.11.01



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MMR SD-5 Scenario 6 Run 11 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD5511P8.DWG
Project No: 01 MMR.01

Drawing No.

S6.11.02

Environmental Consulting Engineers
MMR SD-5 130/130/100
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 130% K field, 130% recharge, and 100% pumping rate.

Recharge = 35.1 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN12

Extraction Wells = 14 (-355 gpm)

- fence: -35x2, -20x9, -30, -35, -40 gpm

Injection Wells = 14 (355 gpm)

- fence: 25x4, 30x5, 25, 20x4 gpm

Plume Capture, SD-5 Mass:

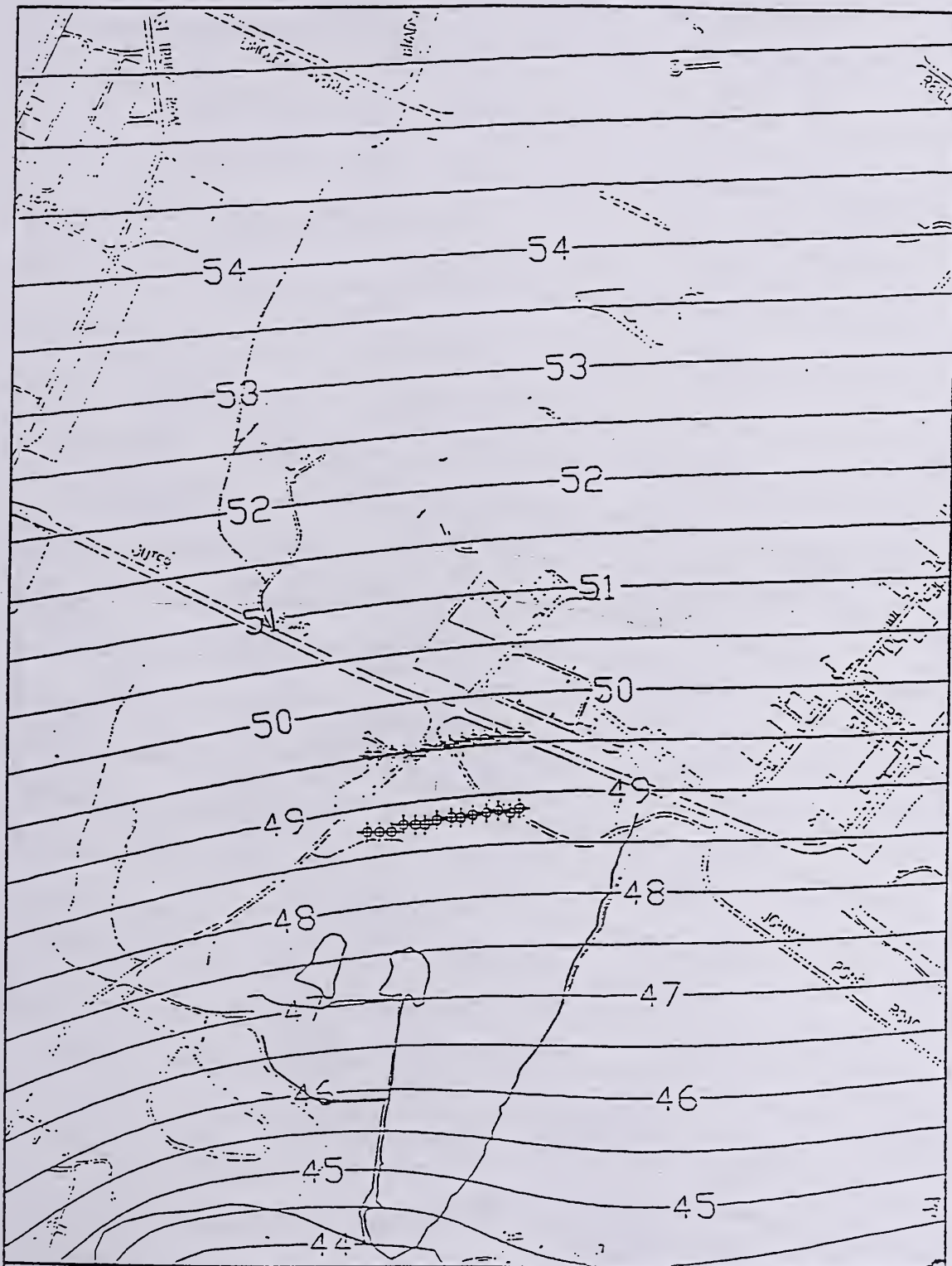
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	3960	94.83%
2.4	1033	2479.2	2306.4	93.03%
1.2	1400	1680	1612.8	96.00%
<i>totals</i>	2607	8335.2	7879.2	94.53%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	39600	94.83%
24	1033	24792	23064	93.03%
2.4	1400	3360	3225.6	96.00%
<i>totals</i>	2607	69912	65889.6	94.25%

Plume Capture, by Volume:

Volume per Particle (ft^3)*	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	21612500	94.74%

* Volume of water per particle using porosity of 35%



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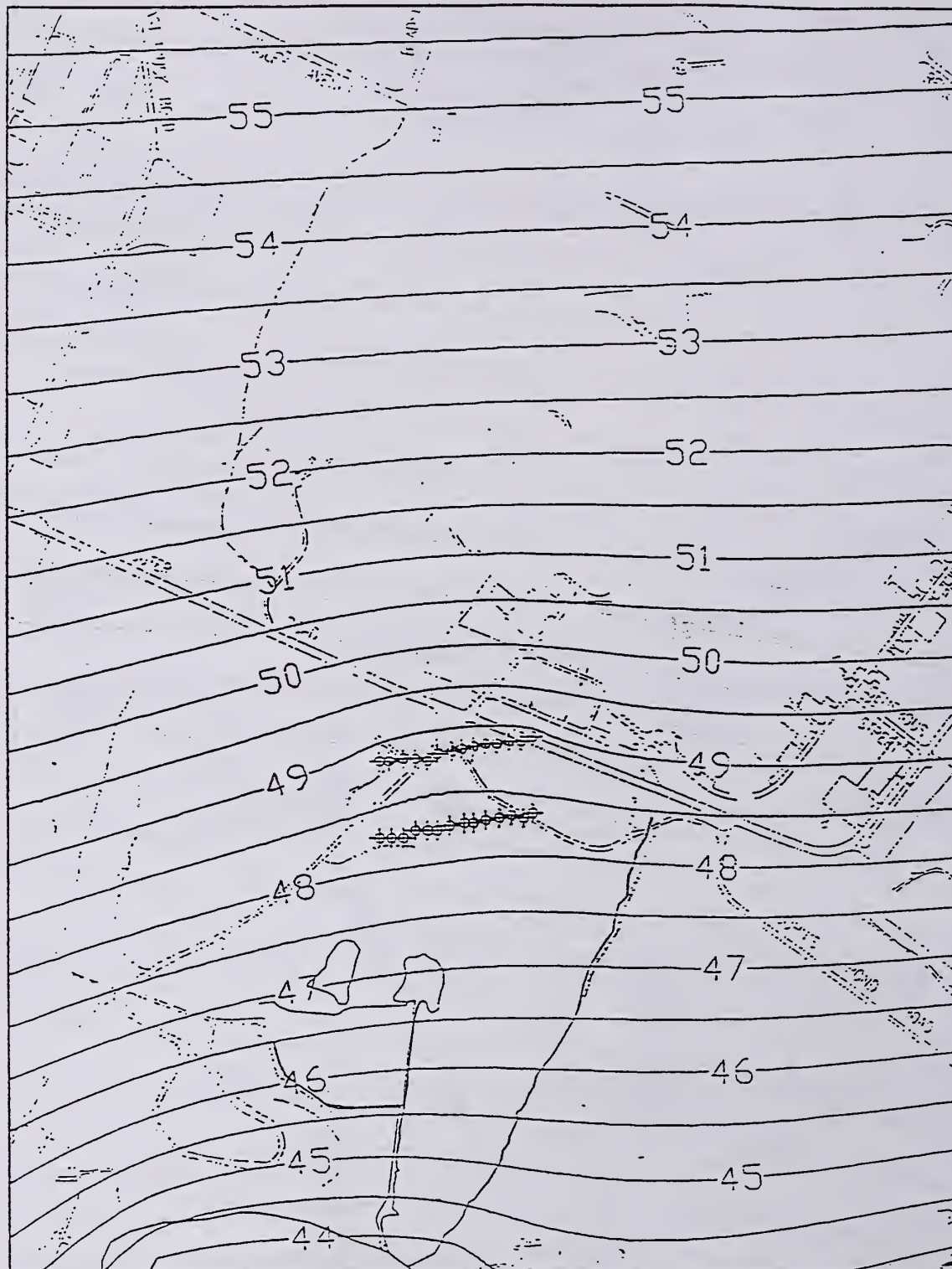
SD-5 Scenario 6 Run 12 SS Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: MLC
Drawing Name: SD512SS.DWG
Project No.: CT MMR.01

Drawing No.

S6.12SS.01



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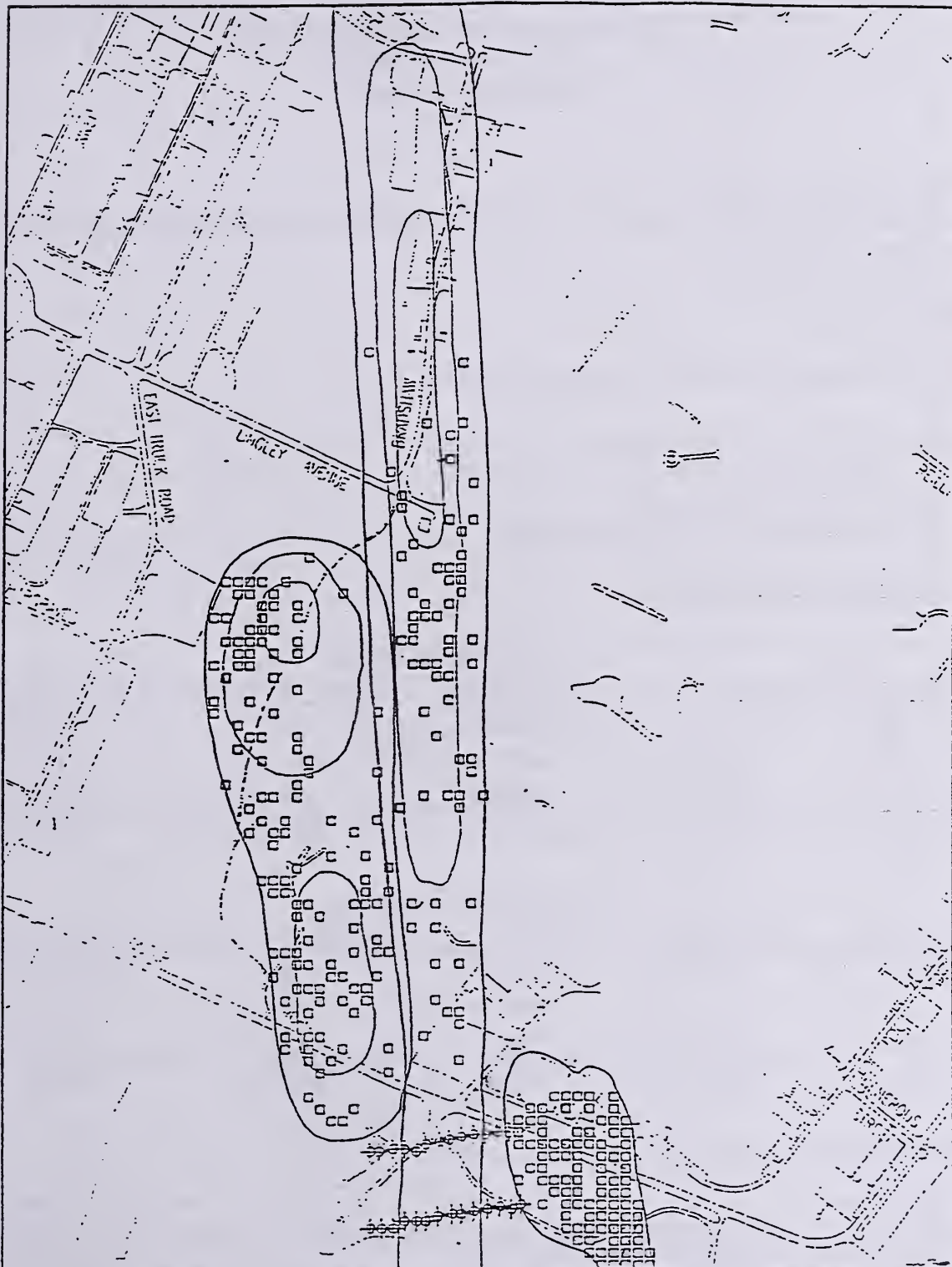
SD-5 Scenario 6 Run 12 (355 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 3
Drawn by: BTH
Checked by: VLC
Drawing Name: SD5612WT.DWG
Project No.: 01 WMR.01

Drawing No.

S6.12.01



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MMR SD-S Scenario 6 Run 12 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No: Rev. 0
Drawn by: MLC
Checked by:
Drawing Name: SD5612P8.DWG
Project No: QT MMR.01

Drawing No.

S6.12.02

Environmental Consulting Engineers
MMR SD-5 130/130/130
Model Run Summary
6-13-96

Model: High K Box Model

Description: ECE defined inputs with 130% K field, 130% recharge, and 130% pumping rate.

Recharge = 35.1 in/yr

K Field = ECE defined.

Nodes = 772421

Elements = 707112

Model Parameters: SD-5 PCS Scenario #6 RUN13

Extraction Wells = 14 (-461.5 gpm)

- fence: -45.5x2, -26x9, -39, -45.5, -52 gpm

Injection Wells = 14 (461.5 gpm)

- fence: 32.5x4, 39x5, 32.5, 26x4 gpm

Plume Capture, SD-5 Mass:

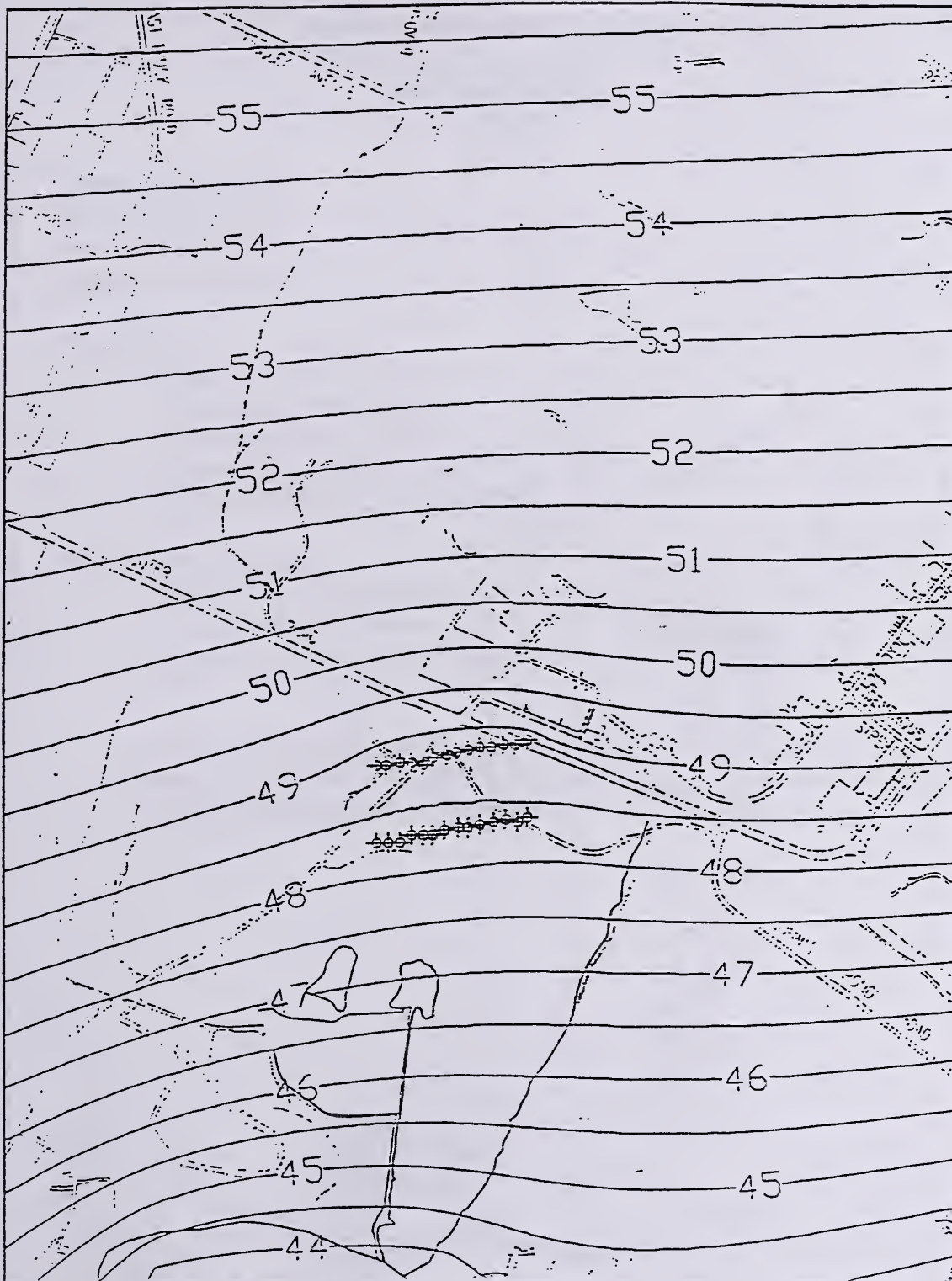
<u>Lower Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
24	174	4176	4128	98.85%
2.4	1033	2479.2	2457.6	99.13%
1.2	1400	1680	1669.2	99.36%
<i>totals</i>	2607	8335.2	8254.8	99.04%

<u>Upper Bound Calculation</u>				
Mass (μg)	# of Particles	Total Mass (μg)	Captured Mass (μg)	% Mass Captured
240	174	41760	41280	98.85%
24	1033	24792	24576	99.13%
2.4	1400	3360	3338.4	99.36%
<i>totals</i>	2607	69912	69194.4	98.97%

Plume Capture, by Volume:

Volume per Particle (ft^3)	# of Particles	Total Volume (ft^3)	Captured Volume (ft^3)	% Volume Captured
8,750	2607	22,811,250	22636250	99.23%

* Volume of water per particle using porosity of 35%



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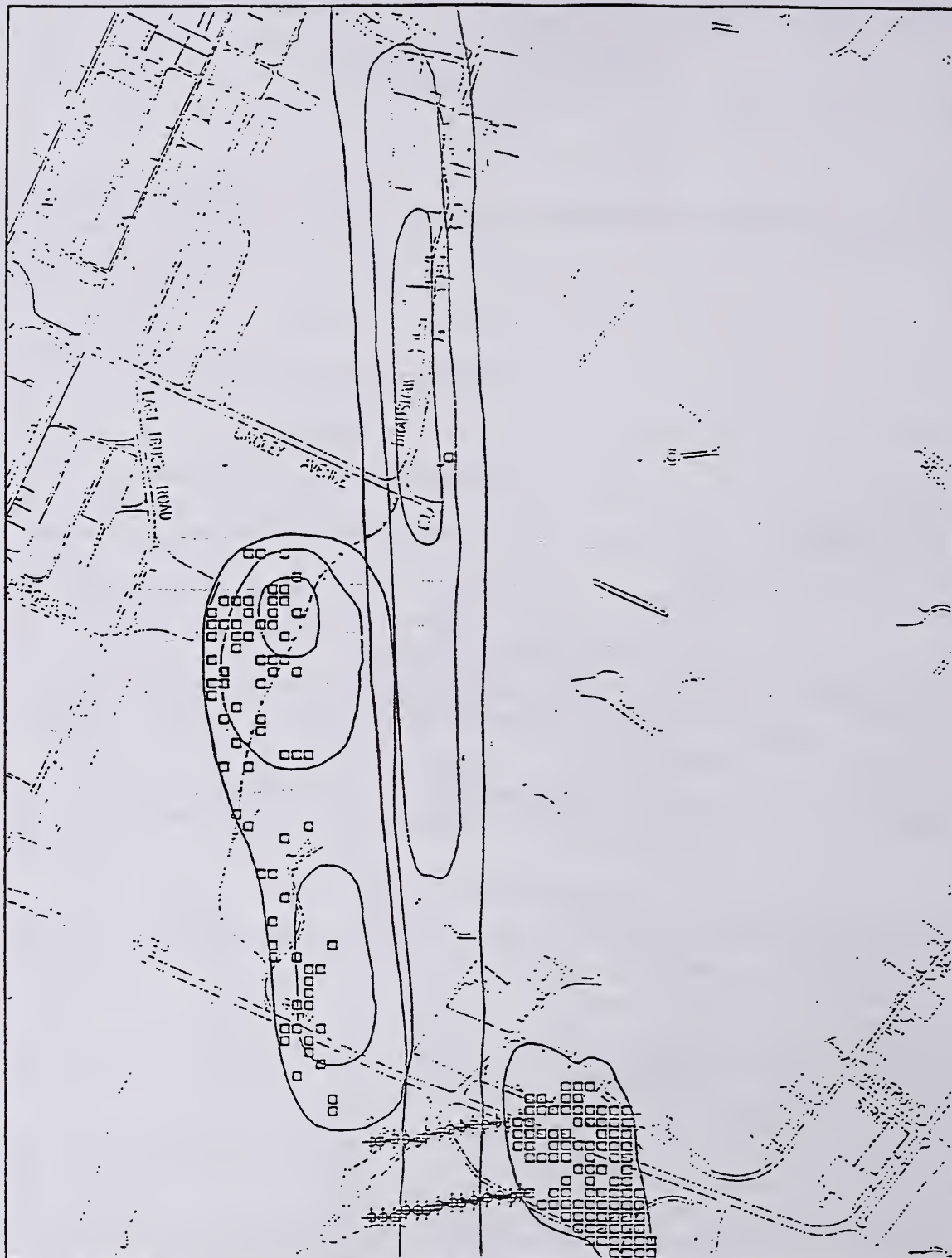
SD-5 Scenario 6 Run 13 (461.5 gpm) Water Table

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: BTH
Checked by: VLG
Drawing Name: SD513WT.DWG
Project No.: 07 MWR.01

Drawing No.

56.13.01



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MWR SD-5 Scenario 5 Run 13 Particles Ending At Boundaries

Massachusetts Military Reservation

Drawing Version No.: Rev. 0
Drawn by: VMC
Checked by:
Drawing Name: SD513P9.DWG
Project No: OT MWR.01

Drawing No.

S6.13.02

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 6D
Model Run Summary
5-20-96

Model: Constant head

Recharge = 29 in/yr

Nodes = 415298

Elements = 378828

Wells = 28

- 3 extraction wells (-20 gpm)
- 8 extraction wells (-25 gpm)
- 3 extraction wells (-35 gpm)
- 14 injection wells (26.07 gpm)
- TOTAL PUMP RATE = 365 GPM

Plume Particle Capture:

- SD5NORTH: 83.51% capture.
- SD5SOUTH: 1.21% capture.
- Western Aquifarm: 38.53% capture.
- PFSA: 0.45% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 6E
Model Run Summary
5-21-96

Model: Constant head
Recharge = 29 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

- 3 extraction wells (-15 gpm)
- 4 extraction wells (-20 gpm)
- 4 extraction wells (-25 gpm)
- 3 extraction wells (-35 gpm)
- 14 injection wells (23.57 gpm)
- TOTAL PUMP RATE = 330 GPM

Plume Particle Capture:

- SD5NORTH: 84.40% capture.
- SD5SOUTH: 1.21% capture.
- Western Aquifarm: 45.88% capture.
- PFSA: 0.09% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 6F
Model Run Summary
5-21-96

Model: Constant head
Recharge = 37.7 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

- 3 extraction wells (-20 gpm)
- 8 extraction wells (-25 gpm)
- 3 extraction wells (-35 gpm)
- 14 injection wells (26.07 gpm)
- TOTAL PUMP RATE = 365 GPM

Plume Particle Capture:

- SD5N (north): 70.92% capture.
- SD5S (south): 3.57% capture.
- Western Aquifarm: 61.72% capture.
- PFSA: 0.18% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient (Y > 236570) of this line.

Environmental Consulting Engineers
MMR SD-5 PCS Scenario #6 Run 6G
Model Run Summary
5-21-96

Model: Constant head
Recharge = 20.3 in/yr
Nodes = 415298
Elements = 378828

Wells = 28

- 3 extraction wells (-20 gpm)
- 8 extraction wells (-25 gpm)
- 3 extraction wells (-35 gpm)
- 14 injection wells (26.07 gpm)
- TOTAL PUMP RATE = 365 GPM

Plume Particle Capture:

- SD5NORTH: 85.14% capture.
- SD5SOUTH: 6.55% capture.
- Western Aquifarm: 46.51% capture.
- PFSA: 0.98% capture.

NOTE: Minimum northing (Y) value for extraction wells is 236570, thus SD-5 particles originating down gradient from this value are not likely to be captured. 2948 of the 4184 particles are upgradient ($Y > 236570$) of this line.

APPENDIX B

CALCULATIONS AND SKETCHES

CLIENT AND LOCATION OTIS - MMR

UNIT SD-5

ITEM Chemical Concentrations

OBJECTIVE

Develop groundwater chemical concentrations for SD-5 plume extraction well system.

ASSUMPTIONS:

- Divide the plume into areas that affect extraction wells - see attached figures.
- all wells in area related to extraction wells be considered.
- use groundwater chemical data from OPTech data base as of Oct 1, 1996.
- Develop weighted value for each identified chemical.
 - then
 - using chemical concentrations values
 - determine flow of extraction well(s) affected.
 - divide total flow to treatment to get % of flow concentrations

CALCULATIONS AND SKETCHES

CLIENT AND LOCATION OTIS - MMR

UNIT SD-5

ITEM Chemical Concentrations

- odd segments to get concentration
per flow value.

SD-5 P&T SCENARIO 6 EXTRACTION WELLS (-355 gpm)

	EAST Northing	NORTH Easting	Top of Screen Bot (ft msl)	Bottom of Screen Top (ft msl)	Pump Rate (gpm)
14	864620	236220	-40	0	-35.00 - 45
13	864660	236220	-40	0	-35.00 - 45
12	864720	236230	-40	0	-20.00 25
11	864770	236230	-40	0	-20.00 25
10	864820	236220	-40	0	-20.00 25
9	864860	236250	-40	0	-20.00 25
8	864920	236260	-40	0	-20.00 25
7	864960	236270	-40	0	-20.00 25
6	865010	236280	-40	0	-20.00 25
5	865060	236290	-40	0	-20.00 25
4	865110	236290	-40	0	-20.00 25
3	865160	236300	-40	0	-30.00 - 40
2	865210	236300	-40	0	-35.00 - 45
1	865260	236320	-40	0	-40.00 -

Well No.	Oper	Total	Design	ea	Total
9	20	180	25	225	
1	30	30	40	40	
3	35	105	45	135	
1	40	40	50	50	
14		355		450	
		TOTAL	14		450

SD-5 P&T SCENARIO 6 INJECTION WELLS (355 gpm)

	EAST Northing	NORTH Easting	Top of Screen Bot (ft msl)	Bottom of Screen Top (ft msl)	Pump Rate (gpm)
14	864620	235900	-20	20	25.00 - 32
13	864670	235900	-20	20	25.00 - 32
12	864720	235900	-20	20	25.00 - 32
11	864770	235930	-20	20	25.00 - 32
10	864820	235930	-20	20	25.00 - 32
9	864860	235930	-20	20	30.00 - 38
8	864910	235950	-20	20	30.00 - 38
7	864970	235960	-20	20	30.00 - 38
6	865010	235960	-20	20	30.00 - 38
5	865060	235970	-20	20	25.00 - 32
4	865120	235980	-20	20	20.00 - 25
3	865170	235990	-20	20	20.00 - 25
2	865220	235980	-20	20	20.00 - 25
1	865260	236000	-20	20	20.00 - 25

No	Oper	Total	Design	ea	Total
5	25	125	32	160	
5	30	150	38	190	
4	20	80	25	100	
14		355		450	

SD-5 Extraction (14)

9 - 20 GPM $\times 1.2 = 24$ say 25
 1 - 30 36 40
 3 - 35 42 45
 1 - 40 48 50

SD-5 Rejection (14)

4 - 20 GPM } Range 10-30 GPM
 5 - 25
 5 - 30

#GS Filtrate = $420/350 = 1.2$ say 2 + 5 gpm = 2
 Act Carbon = $420/350 = 1.2$ say 2 Triplex

420 GPM (18% SF)
 (VS 540 used before)

Storm Drain - 5 Contaminant Loads

Design Flow rate = 450gpm

Contaminant	Wght. Estimate ppb	Current Design ppb	Hot Spot ppb
1,2-Dichloroethene	-	-	1.2
Benzene	-	0.78	4.5*
Bis(2-Ethylhexyl) phthalate	-	-	20
EDB	-	1.1	0.02*
Ethylbenzene	2	-	37.5*
Iron	243	243	-
Lead	-	-	-
Manganese	44	44	120*
Methylene Chloride	-	0.35	6*
Tetrachloroethene	1.14	-	0.74*
Toluene	.8	-	6.61*
Trichloroethene	BQL	3.8	0.9*
Xylene	4	-	124*

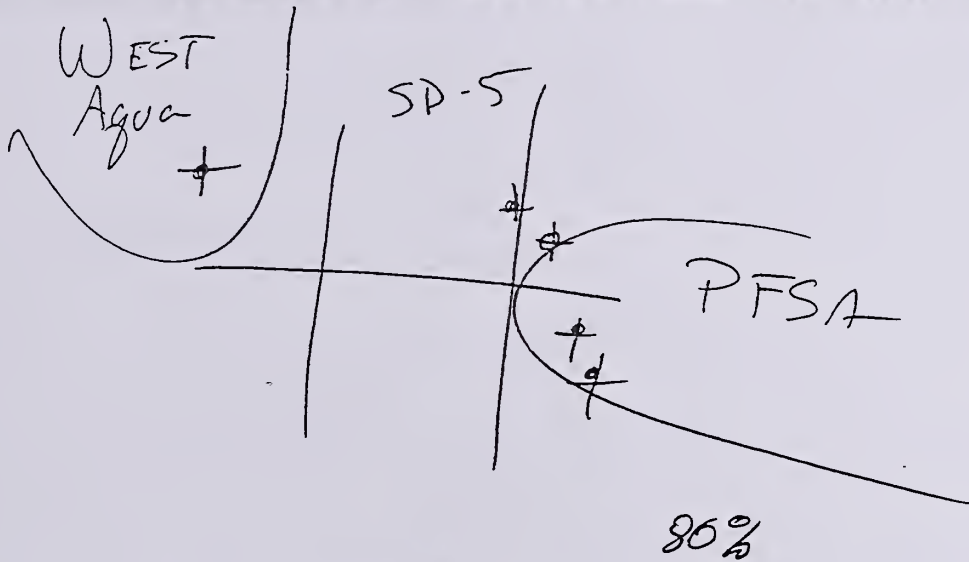
*Values from groundwaters that could be drawn in by the recovery wells

CALCULATIONS AND SKETCHES

CLIENT AND LOCATION OTIS - MMR

UNIT SD-5

ITEM Chemical Concentrations



IFC

APP

IFA

CALCULATIONS AND SKETCHES

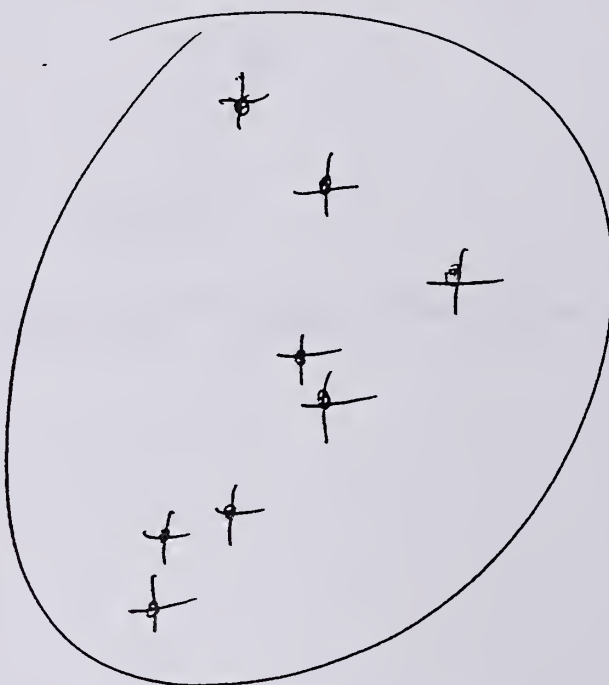
CLIENT AND LOCATION OTIS - MMR

UNIT SD-5

ITEM Chemical Concentrations

Hot Spot

Western Aqua Farm



10%

system flow 450

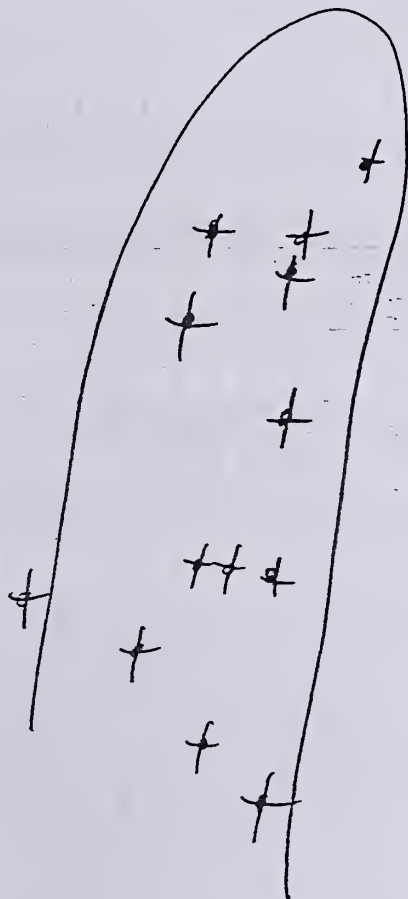
CALCULATIONS AND SKETCHES

CLIENT AND LOCATION OTIS - MMR

UNIT SD-5

ITEM Chemical Concentrations

SD-5
Hot Spot



10%

Septem 450

IFC

APP

IFA

Area	Plume ID	Well ID	Sample ID	Date Analyzed	Lab	Report	Methylene Chloride	1,1,2-Trichloroethene	Tetrachloroethene	Benzene	1,2-Dichloroethene	1,2-Dichloroethene (Total)	o-Xylene	m,p-Xylene	1,2-Dichloroethene (Total)	2-Methyl-2-butene	1,2-Dichloroethene (Total)
1	SD-5	MW-18/SD-5	28MW18XXX	4/13/90	ABB	SERGO AUG. ND		5	10	ND	ND	ND	NA	NA	ND	ND	ND
	SD-5	MW-18C/SD-5	00MWX18XX	5/26/93	ABB	SERGO AUG. ND		5	12	NA	ND	ND	NA	NA	ND	ND	ND
	SD-5	MW-18A/SD-35	28MWX18XX	1/17/96	CAM	DATA BASE	NA	ND	ND	1.2	ND	ND	ND	ND	NA	NA	NA
	SD-5	MW-18B/SD-5	28MWX18XX	1/17/96	CAM	DATA BASE	NA	ND	ND	1.3	ND	ND	ND	ND	NA	NA	NA
	SD-5	MW-18/SD-5	28MWX18XX	1/17/96	CAM	DATA BASE	NA	ND	BQL	1.1	ND	ND	ND	ND	NA	NA	NA
	SD-5	MW-19A/SD-5	28MWX19XX	1/16/96	CAM	DATA BASE	NA	ND	ND	5.9	ND	ND	ND	ND	NA	NA	NA
	SD-5	MW-19Z/SD-5	28MWX19XX	1/17/96	CAM	DATA BASE	NA	ND	ND	1.7	BQL	ND	ND	ND	NA	NA	NA
2	SD-5	MW-20A/SD-5	28MWX20XX	1/18/96	CAM	DATA BASE	NA	ND	BQL	2	ND	ND	ND	BQL	ND	NA	NA
	SD-5	MW-20U/SD-5	28MWX20XX	1/18/96	CAM	DATA BASE	NA	ND	ND	5	ND	ND	ND	ND	NA	NA	NA
	SD-5	MW-20/SD-5	28MWX20XX	1/18/96	CAM	DATA BASE	NA	ND	ND	1.1	ND	ND	ND	17.0	NA	NA	NA
5	SD-5	MW-10/SD-5	28MW10XXX	4/11/90	ABB	SERGO AUG. ND	ND	NA	ND	28	ND	ND	NA	NA	ND	ND	22
	SD-5	MW-10/SD-5	28MW10XXX	5/17/93	ABB	SERGO AUG. ND	NA	NA	6J	0.3J	ND	ND	NA	NA	2	ND	ND
	SD-5	MW-11/SD-5	28MW11XXX	4/10/90	ABB	SERGO AUG. ND	NA	NA	15	NA	ND	ND	NA	NA	ND	ND	ND
	SD-5	MW-12/SD-5	28MW12XXX	5/17/93	ABB	SERGO AUG. ND	NA	NA	ND	NA	ND	ND	NA	NA	ND	ND	ND
	SD-5	MW-12/SD-5	28MW12XXX	4/10/90	ABB	SERGO AUG. ND	NA	NA	28	2	ND	ND	NA	NA	ND	ND	36
	SD-5	MW-13/SD-5	28MW13XXX	4/10/90	ABB	SERGO AUG. ND	NA	NA	17	2	ND	ND	NA	NA	ND	ND	8J
	SD-5	MW-15/SD-5	28MW15XXX	5/18/93	ABB	SERGO AUG. ND	NA	NA	ND	1	ND	ND	NA	NA	ND	ND	ND
	SD-5	MW-15/SD-5	28MW15XXX	4/13/90	ABB	SERGO AUG. ND	NA	NA	ND	6J	ND	ND	NA	NA	ND	NA	NA
	SD-5	MW-9/SD-5	28XX9XXX93	5/17/93	ABB	SERGO AUG. ND	NA	NA	13	5	ND	ND	NA	NA	2	ND	ND
	SD-5	MW-9/SD-5	28MW9XXX	4/11/90	ABB	SERGO AUG. ND	NA	NA	11J	4J	ND	ND	NA	NA	4J	ND	10
	SD-5	MW-15/SD-5	28MWX15XX	1/19/96	CAM	DATA BASE	NA	ND	BQL	2.2	BQL	ND	ND	ND	NA	NA	NA
	SD-5	MW-4/SD-5	28MWXX4XX	5/17/93	ABB	SERGO AUG. 11	NA	NA	ND	NA	ND	ND	NA	NA	110	ND	ND
	SD-5	MW-4/SD-5	28MW4XXX	4/11/90	ABB	SERGO AUG. NA	NA	NA	270J	ND	ND	ND	NA	NA	300	ND	ND
	SD-5	MW-4/SD-5	28MW4XXX	4/11/90	ABB	SERGO AUG. NA	NA	ND	82.0	ND	ND	ND	NA	NA	200J	ND	ND
	SD-5	MW-4/SD-5	28MWXX4XX	1/19/96	CAM	DATA BASE	NA	1.2	61.0 E	1.7	BQL	ND	ND	ND	NA	NA	NA
	SD-5	MW-6/SD-5	28MWXX6XX	1/18/96	CAM	DATA BASE	NA	NA	1	0.4J	ND	ND	NA	NA	NA	NA	NA
	SD-5	MW-6/SD-5	28MW6AXX	5/18/93	ABB	SERGO AUG. ND	NA	NA	4	ND	ND	ND	NA	NA	1	ND	ND
	SD-5	MW-6/SD-5	28MW6AXX	4/10/90	ABB	SERGO AUG. ND	NA	NA	8	ND	ND	ND	NA	NA	2	ND	ND
	SD-5	MW-6/SD-5	28MWXX6XX	5/18/93	ABB	SERGO AUG. ND	NA	NA	99	ND	ND	ND	NA	NA	12	ND	ND
	SD-5	MW-6/SD-5	28MW6XXX	4/10/90	ABB	SERGO AUG. ND	NA	NA	6	BQL	ND	ND	NA	NA	73	ND	ND
	SD-5	MW-6/SD-5	28MWXX6XX	1/19/96	CAM	DATA BASE	NA	ND	26.0	1.7	BQL	ND	ND	ND	NA	NA	NA
	SD-5	MW-6/SD-5	28MWXX6XX	1/19/96	CAM	DATA BASE	NA	BQL	26.0	1.6	BQL	ND	ND	ND	NA	NA	NA
	SD-5	MW-6/SD-5	28MWXX6XX	1/18/96	CAM	DATA BASE	NA	BQL	26.0	1.6	BQL	ND	ND	ND	NA	NA	NA
* Wells also included in Western Aquafarm Spreadsheet																	15

Area	Plant ID	Well ID	Sample (SIS) Code	Date Analyzed	Lab	Report	Methylene Chloride	1,2-Dichloroethane	Trichloroethane	Tetrachloroethylene	Benzene	Toluene	Ethylbenzene	m,p-Xylene	o-Xylene	Total Xylenes	1,2-Dibromoethane (EDB)	1,1,1-Trichloroethane
1	Western Aquafarm	MW-573	21MW573XX	11/28/95	CAM	DATA BASE	ND	1.4	.9	ND	ND	ND	BQL	ND	ND	NA	ND	BQL
	Western Aquafarm	MW-573	21MW573XX	11/28/95	CAM	DATA BASE	ND	1.4	.9	ND	ND	ND	BQL	ND	ND	NA	ND	BQL
2	WESTERN AQUA	MW-20A/SD-5	01MW20XA9	5/27/93	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	2	ND	ND
	WESTERN AQUA	MW-20A/SD-5	01MW20XA9	5/27/93	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	2	ND	ND
	WESTERN AQUA	MW-20B/SD-5	01MW20XB9	5/27/93	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	2	ND	ND
	Western Aquafarm	MW-20A/SD-5	28MWX20XX	4/23/90	ABB	DATA BASE	ND	NA	ND	ND	ND	3 J	ND	NA	NA	2 J	ND	ND
	Western Aquafarm	MW-20A/SD-5	28MWX20XX	8/22/95	CAM	DATA BASE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	.01 R	NA
	Western Aquafarm	MW-20A/SD-5	28MWX20XX	7/6/95	CAM	DATA BASE	ND	ND	ND	BQL J	ND	ND	ND	ND	ND	NA	0.03 R	ND
	Western Aquafarm	MW-20B/SD-5	28MWX20XX	7/7/95	CAM	DATA BASE	ND	NA	ND	0.74	ND	ND	ND	ND	ND	NA	0.07 R	ND
	Western Aquafarm	MW-20/SD-5	28MWX20XX	4/25/90	ABB	DATA BASE	6 X	NA	ND	ND	ND	14 J	ND	NA	NA	64 J	ND	ND
	Western Aquafarm	MW-20/SD-6	01MWX20XX	5/27/93	ABB	DATA BASE	6 X	NA	ND	ND	ND	14 J	ND	NA	NA	2	ND	ND
	Western Aquafarm	MW-20/SD-6	28MWX20XX	8/16/95	CAM	DATA BASE	ND	ND	ND	ND	.5	BQL	1.1	2.8	16	NA	.03	ND
	Western Aquafarm	MW-21/SD-6	28MWX21XX	4/23/90	ABB	DATA BASE	ND	NA	ND	ND	ND	3 J	ND	NA	NA	3 J	ND	ND
	Western Aquafarm	MW-21/SD-5	28MWX21XX	12/30/94	QM	DATA BASE	NA	NA	ND	ND	ND	ND	1.3	NA	NA	2.5	NA	ND
	Western Aquafarm	MW-21/SD-5	28MWX21XX	8/22/95	CAM	DATA BASE	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	.02 R	NA
	Western Aquafarm	MW-21/SD-5	28MWX21XX	7/6/95	CAM	DATA BASE	ND	NA	ND	ND	ND	6.88 J	70.0 J	91.0 J	130.0J	NA	0.13 R	ND
3	WESTERN AQUA	MW-16/SD-5	28MW16XXX	4/10/90	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	100J	ND	ND
	WESTERN AQUA	MW-17/SD-5	28MW17XXX	4/10/90	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	2500J	ND	ND
	WESTERN AQUA	MW-17/SD-5	28MW17XXX	4/10/90	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	1400J	ND	ND
	Western Aquafarm	MW-2/FTA-2	39MWXX2XX	10/30/95	CAM	DATA BASE	ND	ND	ND	BQL	6.9	26.0	200.0	780.0	350.0	NA	ND	ND
	Western Aquafarm	MW-2/FTA-2	39MW2XXX	4/10/90	ABB	DATA BASE	ND	NA	ND	ND	ND	ND	ND	NA	NA	900J	ND	ND
	Western Aquafarm	MW-2/FTA-2	39MWXX2XX	5/19/93	ABB	DATA BASE	ND	NA	ND	ND	ND	ND	910	NA	NA	5600	ND	ND
4	Western Aquafarm	MW-2/SD-5	28MW2XXX	4/13/90	ABB	DATA BASE	ND	NA	ND	ND	ND	ND	ND	NA	NA	ND	ND	ND
	Western Aquafarm	MW-2A/SD-5	28MWX2XX	7/7/95	CAM	DATA BASE	ND	NA	ND	.6	ND	ND	ND	ND	ND	NA	.1 R	ND
	WESTERN AQUA	MW-3/FTA-2	39MW3XXX	4/4/90	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	ND	NA	NA	37J	NA	ND
	WESTERN AQUA	MW-3/FTA-2	39MWX3XX	5/19/93	ABB	SERGOU AUG. 9	ND	ND	0.20J	0.20J	ND	ND	12	NA	NA	65	ND	ND
	WESTERN AQUA	MW-4/FTA-2	39MWX4XX	5/20/93	ABB	SERGOU AUG. 9	ND	ND	1	0.40J	ND	ND	11	ND	NA	65	ND	ND
	Western Aquafarm	MW-5A/FTA-2	39MWX5XX	7/6/95	CAM	DATA BASE	ND	NA	ND	ND	ND	BQL J	4.32 J	BQL J	0.51 J	NA	0.1 R	ND
	WESTERN AQUA	MW-5/FTA-2	39MWX5XX	5/20/93	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	190	NA	NA	780	ND	ND
	WESTERN AQUA	MW-5/FTA-2	39MWX5XX	5/20/93	ABB	SERGOU AUG. 9	ND	ND	ND	NA	ND	ND	190	NA	NA	750	ND	ND

Western Aquafarm

Dibromochloromethane	Isopropylbenzene	Propylbenzene	1,3,5-Trimethylbenzene	tert-Butylbenzene	1,2,4-Trimethylbenzene	sec-Butylbenzene	Isopropylbenzene	n-Butylbenzene	1,2,4-Trichlorobenzene	naphthalene	1,2,3-Trichlorobenzene	1,2-Dichlorobenzene (Total)	Methylphenyl ether	bis(2-Ethylhexyl)phthalate	Phenylglycidyl ether	Dimethylphenyl ether	4-Methylphenyl ether	Acetophenone	Dibenzofuran	Diethylphthalate	Fluorene	Phenanthrene
BQL	ND	ND	ND	0.5	ND	ND	ND	1.4	BQL	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
BQL	ND	ND	ND	BQL	ND	.6	ND	1.3	BQL	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	0.74 J	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	BQL	ND	ND	ND	BQL	ND	9.2	ND	ND	ND	NA	13	ND	1J	NA	NA	NA	NA	NA	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	ND	ND	NA	ND	ND	ND	ND	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ND	ND	9.22 J	32.0 J	ND	30.0 J	ND	ND	27.0 J	ND	6.8 J	ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	ND	ND	8J	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	NA	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	BQL	14.0	75.0	ND	250.0	5.4	5.4	46.0	1.6	42	1.2	NA	NA	5J	NA	NA	NA	NA	NA	NA	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	72	NA	ND	8J	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	150J	NA	ND	16	ND	ND	7J	ND	ND	ND	ND	ND	ND
ND	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	ND	ND	25	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA	NA	8J	ND	NA	11	ND	NA	NA	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	3J	NA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	NA	9.78 J	ND	ND	1.09 J	0.78 J	0.56 J	6.40 J	ND	3.02 J	ND	NA	NA	ND	ND	NA	NA	NA	NA	NA	NA	NA
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	110	NA	21J	83	ND	ND	ND	ND	3J	2J	1J	3J	3J
ND	NA	NA	NA	NA	NA	NA	NA	NA	ND	110	NA	20J	83	ND	ND	3J	ND	ND	2J	ND	3J	3J

* Wells are also included in SD-5 Spreadsheet

Area	Plume ID	Well ID	Sample ID	Date Analyzed	Lab	Report	Enthalpy	Total Xylenes	Bulk	Diethyl	Phenyl	Phenyl	Phenyl	Phenyl	Pyrene	Chrysene	Benzo(b) Fluoranthene	Indeno(1,2,3-cd)pyrene	Benzo(g,h,i)perylene
1	PFSA	MW-306	24MW306XX	5/27/93	ABB	SEGOU AUG. 91 ND	ND	ND	NA	ND	1J	3J	ND	2J	1J	2J	1J	1J	1J
	PFSA	MW-307	24MW307XX	9/7/89	ABB	SEGOU AUG. 91 18J	550J	550J	11J	10	ND	ND	ND	ND	ND	ND	ND	ND	ND
	PFSA	MW-307	24307XXX93	5/24/93	ABB	SEGOU AUG. 91 ND	ND	ND	ND	ND	ND	ND	26	ND	ND	ND	ND	ND	ND
	PFSA	MW-317	24MW317XX	2/28/90	ABB	SEGOU AUG. 91 ND	ND	ND	ND	52	ND	ND	ND	ND	ND	ND	ND	ND	ND

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APPENDIX C



September 12, 1996

Calgon Carbon Corporation
for
Jacobs Engineering Group, Inc.
Environmental Division
4848 Loop Central Drive
Houston, Texas 77081

Carbon Adsorption System Design: OTIS ANGB

To aid Jacobs Engineering in the selection of the most cost effective treatment system for remediation of the contaminated plumes located at the OTIS Air National Guard Base in Massachusetts, Calgon Carbon Corporation has developed the following report.

A. Fuel Spill 12 Site

There are two contaminated plumes at the OTIS ANGB site to remediate. The first plume to be address is the Fuel Spill 12 which will have a treatment flowrate of 1015 gpm. We have investigated three (3) options for treatment at the Fuel Spill 12 Site:

1. Current Specified System- 3-2 Stage Systems following UV-OX

The current specified design is three (3) UV/OX units followed by carbon polishing utilizing three (3) Model 10 Carbon Adsorption Systems. The Model 10 system is a dual bed carbon adsorption system, each bed having a carbon capacity of 20,000 lbs, with 8" diameter interconnecting process and backwash piping and 4" diameter carbon fill and discharge piping. The interconnecting piping arrangement allows for series and/or parallel operation of each Model 10 unit. For this particular treatment pattern each unit will handle a flowrate of 338 gpm and will be operated in series and will follow UV/OX treatment. This represents a contact time of 15 minutes per stage, or 30 minutes total which is more than adequate for adsorption of low levels of VOC's. Accordingly UV/OX treatment is expected to remove the organic compounds down to a carbon polishing level of ethylene dibromide 4.2 ppb and benzene 2.2 ppb. Based on these influent concentrations to the carbon polishing system the calculated carbon use rate is 0.03 lbs/1000 gallons which would result in an annual carbon consumption of 16,000 pounds. However because of the relative inaccuracy when predicting use rates at extremely low levels a realistic carbon use rate of 0.1 lbs/1000 gallons is recommended. This will result in a use rate of about 54,000 pounds per year, or one carbon changeout per year. The following table summarizes capital and operating costs for the Current System Design:

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for Three (3) Model 10 Systems
(3) Model 10's - 125 psig - 8" pipe	\$54,000	\$430,000

The specified system design has considerable excess capacity. As discussed in the Alternative Design, a viable design would reduce the system to two (2) Model 10 Systems. The above specified system would have the following advantages:

- 1)Flexibility: The specified system has additional flow capacity, and can handle up to 50% more flow and still be within normal process design parameters.
- 2)Reliability: Full train redundancy. The entire design flow can be managed by two trains as described below, then a train could be down for maintenance and full flow could still be treated.
- 3)Operation: There is extended time between carbon exchanges (on-line time) by having 50% more carbon on-line than would be required by normal process design parameters.

It should be noted that we also investigated carbon treatment without the use of UV/OX an the calculated carbon burn rate was 0.5 lbs/1000 gallons utilizing the use of three (3) model 10 systems. The usage rate was determined by assuming that the unidentified TOC of 6 ppm was comprised of normal encountered hydrocarbons from gasoline. This usage rate estimate therefore, is highly speculative. The following table summarizes the findings:

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for Three (3) Model 10 Systems
(3) Model 10's - 125 psig - 8" pipe	\$267,000	\$430,000

2. Alternative #1A - 2-2 Stage Systems following UV/OX

This option deals with treatment of the waters with the use of two (2) Model 10 systems after UV/OX treatment. Each Model 10 system will be designed to handle half the 1015 gpm or about 507 gpm and will operate in series. This will allow for about 10 minutes contact time per bed or 20 minutes per system and is more than adequate for these organic and their influent levels of contaminant concentration. The annual operating costs for this systems reflecting carbon usage will be identical to the specified option above, however, the capital costs would be considerably less. In addition this particular design allows for additional capacity and flexibility if the influent concentration and/or flowrate were to vary. The pricing and annual operating cost for this alternative is summarized below:

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for Two (2) Model 10 Systems
(2) Model 10's - 125 psig - 8" pipe	\$54,000	\$290,000

The 2-Model 10 System would be the design recommended by Calgon Carbon if two-stage treatment were mandated by the client. This design meets process design requirements such as contact time per stage (10 minutes) and surface loading rates (6.5 gpm/sf). The system will also result in a moderate pressure drop to allow direct pumping from the well, through the adsorption system and into the distribution system.

Advantages of the use of two Model 10 systems following UV/OX is:

- 1) Flexibility: There is still an additional flow capacity of up 20% excess, which would still maintain contact times > 7 minutes per stage.
- 2) Operation: Optimize carbon consumption because of series operation for low level VOC applications. The carbon usage will not be any less than for the specified design.
- 3) Effluent Quality Assurance: The two stage design still maintains a complete second stage on-line to assure effluent quality.

This first alternative can very easily be incorporated into the specified design without additional design costs by merely eliminating one of the Model 10 system from the Scope Of Work. The 3rd System could be maintained on all drawings and layouts as a "dotted line" or "shadow" item for possible additions later should flow requirements increase.

3. Alternative #2A - 2-1 Stage System following UV/OX

The cost effective option from a capital standpoint for treatment of the Fuel Spill 12 area is with the use of one (1) Model 10 System connected for parallel use only. Each vessel will handle 507 gpm and will provide 10 minutes of contact time and provide single stage carbon polishing. The adsorption system will follow UV/OX treatment and will essentially act as a second stage in the UV/OX-Carbon treatment scheme. In-bed sample taps located at three (3) different locations in the carbon bed of each vessel will allow sampling throughout the carbon bed to assure that break through does not occur. Single stage carbon treatment has been accepted by many Potable Water Systems such as Suffolk County Water Authority, City of Modesto and City of Rockford. The capital cost for this alternative is the most economical and the annual carbon consumption will be within +/- 20% of the above two options which utilize multiple systems. As described under the first two options, the usage rate for economic analyses is recommended to be 0.1 lbs/100 gallons, so the usage rate for the single stage treatment would not be expected to be substantially different.

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for One (1) Model 10 System
(1) Model 10's - 125 psig - 8" pipe	\$54,000 +/- 20%	\$145,000

The single stage system design would be recommended by Calgon Carbon for treatment where minimization of capital is required.

The advantages to the use of one (1) Model 10 system following UV/OX is:

- 1) Cost: Most cost effective design still providing ample contact time. Single stage design has been accepted by many potable water systems
- 2) Monitoring: The downflow fixed bed design allows for the adsorption zone to move through the bed in a plug flow manner, so protection of effluent quality using the carbon adsorption process is still assured.
- 3) Total Treatment Costs: Considering both capital and operating costs, the single stage design provides the lowest overall treatment costs.

B. Storm Drain #5 Site

Further analyses on the Storm Drain #5 location having a treatment flowrate of 450 gpm and utilizing carbon treatment resulted in the following options:

1. Current Specified System - 2-2 Stage Carbon Adsorption Systems (Carbon Only)

The current treatment scheme involves two (2) Model 10 systems each operating in a series operating mode and handling a 225 gpm flowrate. This represents a contact time of 23 minutes per stage or > 45 minutes total. Contaminants in the drain waters includes methylene chloride at an influent concentration of 0.35 ppb. Methylene chloride is difficult to removal and the carbon use rate is difficult to evaluate. The usage rate to remove methylene chloride to non-detectable levels is estimated to be 1.24 lbs/1000 gallons or 294,000 lbs/year. However, based on this in fluent concentration to the carbon system the calculated carbon use rate estimate for removal without methylene chloride removal the usage rate is 0.021 lbs/1000 gallons which would result in an annual carbon consumption of 5,000 pounds. However a carbon use rate of 0.1 lbs/1000 gallons was used. This will result in a use rate of about 24,000 pounds per year, or one carbon change out per 20 months. The following TABLE presents the Capital costs for the system and the annual operating costs with and without methylene chloride removal.

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for Two (2) Model 10 Systems
(2) Model 10's - 125 psig - 8" pipe - With methylene chloride removal	\$294,000	\$290,000
(2) Model 10's - 125 psig - 8" pipe - Without methylene chloride removal	\$24,000	\$290,000

The specified system design for the storm drain #5 has considerable excess capacity. As discussed above, a viable design would reduce the system to one (1) Model 10 System. The above specified system would have the following advantages:

- 1)Flexibility: The specified system has additional flow capacity, and can handle up to 50% more flow and still be within normal process design parameters.
- 2)Reliability: Full train redundancy. The entire design flow can be managed by two trains as described below, then a train could be down for maintenance and full flow could still be treated.
- 3)Operation: There is extended time between carbon exchanges (on-line time) by having 50% more carbon on-line than would be required by normal process design parameters.

2. Alternative #1B - 1-2 Stage System followed by UV/OX

This option considered one (1) Model 10 system connected for series operation treating the 450 gpm flowrate with an estimated 5 psi pressure drop (based on clean filtered waters) followed by UV/OX treatment for removal of the methylene chloride. Carbon adsorption will remove all contaminants except for methylene chloride. The UV/OX process will be more effective removing methylene chloride without the competition from the other organic compounds. The contact time will be about 12 minutes per bed or 24 minutes for the series operated system. The predicted carbon use rate is based on the Trichloroethylene (TCE) carbon use rate which was calculated as 0.021 lbs/1000 gallons. However as before a carbon use rate of 0.1 lbs./1000 gallons was used for conservative purposes. The Capital and annual operating costs for this scenario are as follows:

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for One (1) Model 10 System
(1) Model 10's - 125 psig - 8" pipe	\$24,000	\$146,000

The 1-Model 10 System would be the design recommended by Calgon Carbon if two-stage treatment were mandated by the client. This design meets process design requirements such as contact time per stage (12 minutes) and surface loading rates (5.7 gpm/sf). The system will also result in a moderate pressure drop to allow direct pumping from the well, through the adsorption system and into the distribution system.

Advantages of the use of one Model 10 systems following UV/OX is:

- 1)Flexibility: There is still an additional flow capacity of up 20% excess, which would still maintain contact times > 7 minutes per stage.

- 2)Operation: Optimize carbon consumption because of series operation for low level VOC applications. The carbon usage will not be any less than for the specified design.
- 3)Effluent Quality Assurance: The two stage design still maintains a complete second stage on-line to assure effluent quality.

3. Alternative #2B - Single Stage System followed by UV/OX

The most cost effective option for treatment of the Storm Drain #5 area is with the use of one (1) Model 10 Single vessel with 20,000 pounds of virgin granular activated carbon on-line. The single vessel will handle 450 gpm and will provide 12 minutes of contact time. The vessel will precede UV/OX treatment and will remove all compounds except for the methylene chloride. The methylene chloride will be remove by the UV/OX system. In addition the UV/OX unit will serve as a second stage in the treatment process to protect effluent water quality. The carbon adsorber bed will be designed with in-bed sample ports to allow the carbon bed to be run close to full utilization and maintain design effluent water quality. The capital and annual operating costs is as follows:

Specified System	Annual Operating Costs @ \$1.0/lb carbon	Capital Costs for One (1) Model 10 Single Vessel
(1) Model 10 Single Vessel - 125 psig - 8" pipe	\$24,000	\$80,000

The advantages to the use of the single stage Model 10 system followed by UV/OX is:

- 1)Cost: Most cost effective design still providing ample contact time with in-bed sampling possible. In addition UV/OX will act as a second stage to protect effluent quality.
- 2)Monitoring: The downflow fixed bed design allows for the adsorption zone to move through the bed in a plug flow manner, so protection of effluent quality using the carbon adsorption process is still assured.
- 3)Total Treatment Costs: Considering both capital an operating costs, the single stage design provides the lowest overall treatment costs.

In all the above analyses the capital costs for the systems included carbon freight, equipment freight, installation supervision, initial fill supervision and start-up training. In addition the annual operating costs included carbon exchange, provided carbon acceptance has been established, performed by Calgon Carbon Corporation taking responsibility for complete removal of spent carbon and replacement with fresh virgin granular activated carbon using hydraulic transfer.

Specifications and drawings (flow diagram, plan view, elevation view, footprint and assembly drawing) have been included as part of this information package.

C. GENERAL DISCUSSION: CARBON ADSORPTION PROCESS RELATIVE TO OTHER TREATMENT TECHNOLOGIES

The preceding Sections presented Capital and Operating Costs, and relative advantages to different process designs for Alternative Carbon Adsorption System Designs for the two sites at Otis ANGB.

This discussion will discuss design features and advantages of the carbon adsorption process relative to other water treatment processes, rather than between different adsorption system designs.

1) ACCEPTANCE

Adsorption with Activated Carbon is one of the most widely used treatment technologies for potable water systems. The Safe Drinking Water Act Amendments of 1986 established activated carbon treatment as the "yardstick" by which other treatment technologies are to be evaluated in the control of synthetic organic chemicals.

2) EFFICIENCY / FLEXIBILITY

Carbon adsorption is generally accepted to be 99+% efficient in the removal of synthetic organic chemicals. If a compound is adsorbable, it is essentially completely removed until the adsorptive capacity of carbon for that contaminant is used up, or the carbon is "spent". The process of adsorption takes place in a "zone" that moves progressively through the carbon bed, until it reaches the bed outlet. The capacity of carbon may be effected by levels and type of contaminants, and the movement of the adsorption zone may be affected by flowrate, but the efficiency will not be affected. Therefore, the adsorption process is highly flexible with regards to changing process conditions; the usage rate may be affected (and thereby operating costs), but the system will not require redesign or modification if process conditions change.

3) SYSTEM CONTROLS

The carbon adsorption system is a downflow fixed bed design. The system can take wide variations in flow conditions, including on-off (demand well) conditions. There is no need to maintain flow control (steady state conditions) prior to the adsorption process. The system receives the well water at design pressures; there is no need to increase the system pressure to have the system effectively treat the water (at added energy / capital costs). There is also no need to have emergency shut down controls to monitor the loss of system components (i.e. blower failure in an airstripper design will cause instantaneous loss of treatment). Generally all that is required is monitoring of system pressure drop, and this is more for maintaining process flow rather than effluent quality.

4) AUXILIARY EQUIPMENT

The carbon adsorption system is a pressurized flow through system, and as such will not require water collection and repumping after treatment. As a downflow fixed media bed, there is also no additional power or control equipment required. As the activated carbon media is replaced when spent, there is no need for media regenerant handling equipment (i.e. resins). There is no need for booster pumps or other pretreatment steps (see referenced sites in Appendix).

5) CONSUMABLES

The only consumable associated with the activated carbon process is the activated carbon itself. The spent activated carbon is removed from the site and sent to a reactivation facility; whereby through the thermal reactivation process the contaminants are thermally destroyed and the activated carbon is reclaimed for reuse - in other processes such as industrial or remedial waste treatment. The cost of the ultimate destruction of the contaminants is included in the cost of replacement carbon.

As the contaminants are managed and destroyed in the handling of the spent carbon, there are no additional costs for media maintenance or contaminant destruction. There are no on-site regenerant streams to either purchase or manage when they are spent. There is no media that will foul and require chemical, acid or caustic cleaning. There is no media or membranes that may foul over time and require complete exchange and associated disposal. The operating costs presented here represent all of the consumables and there are no other hidden charges.

6) SAFETY

The adsorption system is a completely enclosed system, there is no exposed parts, media or chemicals that would require extraordinary safety precautions. The spent carbon is managed in a "closed loop" process whereby the carbon is transferred as a slurry, in hoses, to and from enclosed trailers. There is no need to handle potentially hazardous regenerant or cleaning chemicals at the site.

7) MAINTENANCE

The adsorption system is a fixed media bed, and as such has no moving parts or controls requiring frequent operator attention or maintenance. Maintenance costs are usually proportional to the characteristics of the water to be treated (corrosion) or frequency of carbon exchanges (erosion of lining and piping); so with groundwater being the water to be treated, this maintenance will be very low.



SPECIFICATION (Sample)

Modular Model 10 Adsorption System
using
Granular Activated Carbon
* * *

PART 1 GENERAL

1.01 SECTION INCLUDES

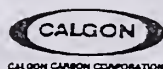
- A. Carbon Adsorption Hardware
- B. Granular Activated Carbon
- C. Manufacturer's Services

1.02 RELATED SECTIONS

- A. _____

1.03 REFERENCES

- A. American Society of Mechanical Engineers (ASME):
 - 1. ASME Section VIII, Division I - American Society of Mechanical Engineers Boiler and Pressure Vessel Code.
 - 2. ASME/ANSI B16.5 American Society of Mechanical Engineers/American National Standards Institute.
 - 3. U.S. Food and Drug Administration, 21 CFR 175.300 and 177.2420.
 - 4. Steel Structures Painting Council Surface Preparation Specifications and National Association of Corrosion Engineers.
 - 5. ASME Section II, American Society of Mechanical Engineers - Materials, Parts A, B, & C.
 - 6. ASTM American Society of Testing Materials.
 - 7. American Waste Water Association (AWWA) B604-90, standard for granular activated carbon.
 - 8. ANSI/NSF Standard Drinking Water System Components - Health Effects.



1.04 DEFINITIONS

GAC - Granular Activated Carbon

GACAS - Granular Activated Carbon Adsorption System

1.05 SYSTEM DESCRIPTION

- A. The Contractor shall furnish and install the Modular Model 10 Carbon Adsorption System described herein. Each system includes the following:
1. Carbon Adsorber (2) with internals for carbon retention
 2. Activated Carbon
 3. Influent, effluent and backwash piping with valves
 4. Carbon fill and discharge piping with valves
 5. Vent and pressure relief piping
 6. Water piping and utility connections
 7. Accessories as shown below
 8. Manufacturers Services.
- B. The vessel(s), piping, valves and carbon functions as a system and shall be the end products of Calgon Carbon Corporation or equal, to achieve standardization for appearance, operation, maintenance, spare parts, and manufacturer's services.
- C. There will be () modular model 10 carbon adsorption systems required, as delineated below:

System #	Quantity	GPM/Adsorber	Pressure Drop	Pressure Drop
			Normal Operation (Maximum)	Backwash (Maximum)
1.				
2.				
3.				



1.06 SUBMITTALS

- A. Submit the following items at the same time under one cover
(____ weeks after receipt of order):
1. Documentation of () GAC water treatment systems completed by the supplier with the following information:
 - a. Description of GA water treatment systems completed by the supplier including flow, system design (operating mode, carbon removal system, etc.), absorber vessel sizing, contaminants treated, and treatment efficiency.
 - b. Reference information including customer name and contact person, phone number, site location, and date of installation.
 2. Provide a description of the proposed adsorption system including flow, contact time, system design, and operating modes.
 3. Provide absorber vessel specification including design pressure, dimensions and capacity.
 4. Provide GACAS flow diagram showing all valuing, components, instrumentation, and service
 5. Provide GACAS general arrangement showing approximate dimensions, weights, and elevations and influent, effluent, backwash, and carbon exchange connection locations.
 6. Provide pressure drop information across system.
 7. Provide description of adsorber vessel GAC loading and removal procedures for system



8. Provide specification of GAC to be utilized in the system. Provide recent lot laboratory analyses results to demonstrate that GAC supply is in accordance with published specifications.
 9. Equipment Performance Bond for 100% of the material and labor costs, F.O.B. _____, for all equipment supplied by the Modular Model 10 Carbon Adsorption System Manufacturer. The bond shall guarantee that all defects or failures will be corrected within the guarantee period of one year and shall remain in force for that period commencing upon final acceptance of the construction contract.
- B. Submit also the following (_____ weeks after receipt of order)
1. Project schedule
 2. Flow schematic drawing
 3. Vessel drawings
 4. Detailed drawings showing equipment arrangement, weights, size, and location of all anchor bolts and nuts, and dimensional setting plan.
 5. Operation and Maintenance Instructions

PART 2 PRODUCTS

2.01 GENERAL

- A. The Contract Documents indicate specific *required* features of the equipment, but do not purport to cover *all* details of design and construction.

2.02 CARBON ADSORBER VESSEL (S)

- A. The carbon adsorber vessel(s) shall be *Modular Model 10 Carbon Adsorption System Vessels*, as supplied by Calgon Carbon Corporation, or equal, which meets these specifications.
- B. The carbon adsorber vessel shall be fabricated of carbon steel, conforming to ASTM A516 grade 70, 10'-0" diameter by 12'-0" straight side height with 2:1 elliptical top and bottom heads. The vessel shall be designed, constructed and



stamped in accordance with ASME Section VIII and registered with the National Board for a design pressure rating of 125 psig (Optional 75 psig) at 140 degrees F. Each vessel will be provided with one (1) 20" diameter round manway located on the lower straight side portion of the vessel and one (1) 14"X18" elliptical manway located on the bottom head. The vessels will be free standing vessels with four (4) structural steel support legs.

- C. The structural aspects of the vessel shall be sufficient to meet the UBC requirements for seismic Zone 4. Manufacturer shall submit detailed calculations illustrating the seismic characteristics of the proposed vessel. Failure to meet this submittal requirement shall invalidate the award.
- D. UNDERDRAIN: Each vessel will be equipped with an internal cone bottom (45 degree angle) underdrain system equipped with polypropylene (ppl) underdrain nozzles to provide a minimum of one (1) nozzle for every nominal square foot of underdrain.
- E. SURFACE PREPARATION: All surfaces will be degreased prior to sandblasting. The adsorber internal surface that will be lined will be blasted to a white metal surface (SSPC-SP5) to provide a 3 to 4 mil anchor pattern. The exterior of the adsorber will be power tool cleaned to the degree specified by SSPC-SP2-63.
- F. LINING: The interior surfaces of each vessel are lined with a nominal 35 to 45 mils dry film thickness (dft) Wisconsin Protective Coatings Plasite "4000 series" lining materials. The interior surfaces under the internal cone bottom will also be lined with 10 to 12 mils dry film thickness (dft) Wisconsin Protective Coatings Plasite "4000 series" materials. Plasite "4000 series" meets the requirements of the U.S. Federal Register, Food and Drug Regulations Title 21, Chapter 1, Paragraph 175.300.
- G. PAINTING: The exterior surface of the adsorbers will be painted to a dry film thickness of 10 - 12 mils with an epoxy mastic (gray color) paint material.

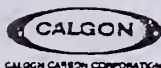


2.03 PROCESS AND UTILITY PIPING

- A. GENERAL: The process and utility piping on the adsorption system will include influent water to the system, treated water and backwash supply and discharge, adsorber vent lines, and granular activated carbon supply and discharge piping.

The influent and effluent piping network allows series (lead/lag) and parallel only flow patterns. Lead/lag flow sequencing allows either; a.) flow from the influent flange, to Adsorber A, to the pipe module, to Adsorber B, to the pipe module then to the effluent flange, or b.) flow from the influent flange, to Adsorber B, to the pipe module, to Adsorber A, to the pipe module to the effluent flange. The change in flow pattern is accomplished with a change of valve positions. The purpose of lead/lag flow sequencing allows an adsorber to act as an on-line backup and/or provides for sufficient contact time to allow adsorption of the contaminants of concern.

- B. PROCESS PIPING: All process piping (influent/effluent and backwash) will be 8" diameter (6" diameter-Optional) constructed of schedule 40 carbon steel, ASTM 53 Grade B materials with cast iron flanged fittings.
- C. VENT PIPING: Vent piping will be 3" diameter constructed of schedule 40 carbon steel, ASTM 53 Grade B materials with cast iron flanged fittings.
- D. CARBON FILL PIPING: Carbon fill piping will be 4" diameter constructed of schedule 40 carbon steel, ASTM 53 Grade B materials.
- E. CARBON DISCHARGE PIPING: Carbon discharge piping will be 4" diameter constructed of schedule 40 polypropylene lined carbon steel ASTM 53 Grade B materials with cast iron flange fittings.
- F. UTILITY PIPING: Utility piping will be threaded schedule 80 carbon steel ASTM A53 Grade B materials.



- G. SURFACE PREPARATION: All piping surfaces will be power tool cleaned to the degree specified by SSPC-SP2-63.
- H. PAINTING: The exterior surface of the piping will be painted to a dry film thickness of 10 - 12 mils with an epoxy mastic (gray color) paint material prior to assembly to ensure minimum oxidation at flanged connections.
- I. PIPING FRAME: The piping network will be provided with a structural steel support frame for support of the piping module.

2.04 PROCESS/UTILITY VALVING

- A. GENERAL: The process and utility piping, excluding GAC fill and discharge piping will be equipped with butterfly valves for flow control. A total of ten (10) 8" diameter (6" diameter-Optional) butterfly valves will be supplied to accommodate the process and backwash control functions. Two (2) valves are needed for backwash control, two (2) valves are needed for influent isolation, two (2) valves for effluent isolation, two (2) for staging of the vessels and two (2) valves for the vent function.
- B. PROCESS VALVES: The main influent, effluent and backwash control valves, will be a cast iron wafer type body, butterfly valve with aluminum-bronze disc, BUNA-N seats and stainless steel shaft to mate to a 150 pound ANSI flanges. The valves are rated for 200 psig in closed position at 180 degrees F, and meet or exceed section 5.0 of AWWA specification C-504-87.
- C. CARBON FILL AND DISCHARGE VALVES: The carbon fill and discharge valves are 4" diameter full port ball valves, 316 stainless steel construction with TFE seats and seals. A total of four (4) valves are supplied. Two (2) for carbon fill and two (2) for carbon discharge.
- D. UTILITY VALVES: Valves for the compressed air supply will be bronze or forge brass or barstock brass body regular port ball valves.



2.05 INSTRUMENTATION

- A. PRESSURE RELIEF: A 3" rupture disk constructed of impervious graphite and designed to relieve pressure at 75% of the MAWP (Optional - 90% of MAWP) will be provided off each vessel vent line to protect the system against overtemperature expansion and extreme system pressure excursions.
- B. DIFFERENTIAL PRESSURE SWITCH: Each vessel will be provided with an indicating differential pressure switch, 4" diameter dial scaled for 20-0-20 psi. A 10 amp switch shall be provided @ 115 volts AC for remote indication, as manufactured by Orange Research Inc. A total of two (2) will be provided with the system.
- C. PRESSURE GAUGES: The process piping will be equipped with pressure gauges to indicate the pressure of water entering and exiting each adsorber and to provide information on pressure drops across each adsorber and the system. The pressure gauges will have 4-1/2" face diameter with a stainless steel bourdon tube in a glycerin filled housing (0-100 psig range). A total of three (3) pressure gauge will be provided with the system.

2.06 MISCELLANEOUS

- A. TRANSFER HOSE CONNECTORS: The carbon piping will be fitted with hose connectors, such that carbon transfer to and from the adsorbers can be facilitated with carbon transfer hoses. These connectors will be 4" Quick Disconnect Adapters constructed of corrosion resistant materials (Nylon) as manufactured by Dover Corporation as Kamlock Connectors or equal.
- B. FLUSH CONNECTIONS: Two (2) flush connections will be provided on each GAC fill line, one upstream and one downstream of the valve, and one flush connection downstream of the GAC discharge valve. Connections will be welded into steel or stainless steel pipe or supplied in solid polypropylene "spacers" for lined pipe. Flush connections will consist of a short section of 3/4" pipe, and a 3/4" full port ball valve and 3/4" quick disconnect adapter to match with water hose fittings.



2.07 GRANULAR ACTIVATED CARBON

A. GENERAL: Product shall be Calgon Carbon Corporation F-300 type carbon, or equal. Twenty thousand (20,000) pounds of Granular Activated Carbon will be provided and installed within each adsorber vessel.

B. GAC SPECIFICATION: The activated carbon will be virgin, granular and manufactured from bituminous coal by a domestic (United States) manufacturing facility. The GAC shall conform to AWWA B604 standards for GAC and comply with the most recent additional ANSI/NSF standard 61. The activated carbon will be Calgon Carbon Corporation Filtrasorb F-300 or equal and conform to the following specifications:

(1)Iodine Number (Maximum)	900
(2)Moisture, wt% as packed, (Maximum)	2
(3)Abrasion Number (Minimum)	75
(4)Effective Size, mm	0.8 - 1.0
(5)Uniformity Coefficient (Maximum)	2.1

U.S. Sieve Series

Percent on 8 mesh (Maximum)	15
Percent thru 30 mesh (Maximum)	4

20,000 pounds initial fill of F-300 carbon per vessel (40,000 pounds total for two (2) vessels).

F-300 type carbon is typically used for (Drinking Water/Waste Water) applications, however other types of carbon can be used within the Single Model 10 system. Contact a Calgon Carbon Corporation Technical Sales Representative for advise on correct carbon selection.

C. GAC ANALYSIS: The delivered activated carbon must be accompanied by an analysis sheet certifying compliance with the specifications, and indicating point of manufacture.



PART 3 EXECUTION

3.01 MANUFACTURER'S SERVICES

- A. A manufacturer's trained specialist, experienced in the installation of the Modular Model 10 Carbon Adsorption System, and with at least five (5) years of field experience shall be present at the job - site and / or classroom designated by the Owner / Contractor for a maximum of () mandays for the following services:

1. Inspection of the installed equipment
2. Supervision of carbon loading
3. Start-up assistance
4. Trouble shooting
5. Operator training

3.02 QUALITY ASSURANCE

- A. The engineer reserves the right to reject acceptance of delivery of any or all pieces of equipment found, upon inspection, to be out of compliance with the tolerances specified in ASME Section VIII, Division I - American Society of Mechanical Engineers Boiler and Pressure Vessel Code. .

END OF SECTION

* * *

CALGON CARBON CORPORATION
CARBON ADSORPTION SYSTEMS FOR OTIS ANGB

APPENDIX ITEMS

- 1) Report on GAC Systems for Potable Water Treatment
- 2) Technical Information - Granular Activated Carbon, Transfer and Reactivation
- 3) Model 10 Adsorption System Specification
- 4) Technical Articles
- 5) Adsorption System Installation References

DESIGN AND OPERATION OF
GRANULAR ACTIVATED CARBON ADSORPTION SYSTEMS FOR
POTABLE GROUNDWATER TREATMENT

The following report has been prepared by Calgon Carbon Corporation for use by customers who have installed granular activated carbon adsorption systems designed and provided solely by Calgon Carbon Corporation.

The report includes the specification of system components, including the granular activated carbon, process design of the adsorption system for removal of typical groundwater contaminants, and the operation and maintenance of the adsorption system.

COMPONENT SPECIFICATION

A. Adsorption System Equipment

The adsorption system equipment is comprised of quality components, constructed to accepted industry standards and specifically intended for potable water treatment to assure both water quality and safety of operation.

Adsorber pressure vessels are constructed and stamped in accordance with ASME code, and all piping is constructed per ASTM standard. The vessel lining is Plasite 4110 vinyl ester coating that is fully acceptable for potable water use under guidelines established by FDA regulation.

The valves in the water system piping meet AWWA requirements for materials of construction and operation. Other components are constructed of either stainless steel or polypropylene, both which are widely used in potable water service.

The adsorption equipment is more fully described in Exhibit 1; System Specification. This adsorption system is also of the same specification as the systems provided under the references in Exhibit 3.

B. Granular Activated Carbon

The granular activated carbon used in the adsorption system is Calgon Carbon's Filtrasorb 300. This activated carbon is manufactured in the United States at Calgon Carbon's Catlettsburg, Kentucky, facility using selected grades of metallurgical grade bituminous coal. This GAC is widely used for potable water treatment for both surface water and groundwater sources, and meets all AWWA and Food Chemical Codex requirements.

The Filtrasorb 300 GAC has the following properties:

- Nominal 8 x 30 mesh size
 - Maximum 15 percent on 8 mesh
 - Maximum 4 percent passing 30 mesh

- 900 minimum iodine number
- 75 abrasion number
- Maximum 1 percent water soluble ash
- Maximum 1 percent total phosphate (as PO_4)

The product bulletin in Exhibit 1 provides more details on Filtrasorb 300.

Filtrisorb 300 is widely used in potable water treatment, and is the referenced groundwater and surface water treatment systems (Exhibit 3). Filtrasorb 300 is also the basis of the process design study work on pressure drop, backwash, and carbon usage rates reviewed in this report and referenced in Exhibit 2.

C. Granular Activated Carbon Transportation Equipment

Calgon Carbon Corporation delivers activated carbon to the system site in a combination of bulk and specialized trailers.

At the manufacturing facility, the virgin grade granular activated carbon is loaded into 1,000 pound capacity "supersacks" for cross-country transportation. These sacks are coded as to lot number and then released for shipment when that lot of granular activated carbon is verified to meet product specification.

On the West Coast, the GAC is transferred in 20,000 pound quantities into specialty designed hopper trailers, maintained by Calgon Carbon solely for the delivery and transfer of carbon used in potable water applications. The trailer is lined with a thin film Plasite vinyl ester resin of the same type used in the adsorber vessel. If the trailer had been used to transfer spent carbon from a potable water plant, it is thoroughly washed before transporting fresh carbon. In no case are these trailers used to transport activated carbon that has been used in non-potable cases. In some cases, the potable trailers may be provided direct from the manufacturing facility.

ACTIVATED CARBON ADSORPTION SYSTEM PROCESS DESIGN

A. Adsorber Vessel Capacity

The adsorber vessels are designed to contain 20,000 pounds (dry weight) of granular activated carbon. This capacity is the same for 10 foot or 12 foot diameter adsorber vessels. This capacity is selected to provide the most cost-effective adsorption system design by enabling the system operator to use proven, pre-engineered adsorption system design and the optimum GAC amount. As GAC which is spent and drained of water will be approximately twice its dry weight (due to retaining water within the granule), the 20,000 pound capacity will be the maximum amount that will be able to be transported away

from the site. Therefore, a single adsorber containing 20,000 pounds of GAC will be compatible with a single transport trailer.

After a minimum contact time is selected as being acceptable for treatment, the adsorption system can then be designed as multiples of the 20,000 pound adsorber vessels to provide the minimum contact time or greater.

B. Empty Bed Contact Time

The empty bed contact time (EBCT) is the time required for the flow per vessel to displace the same volume as taken by the GAC bed. The EBCT is often the basic factor to determine the allowable flow per adsorber.

Calgon Carbon Corporation has done extensive testing and has done surveys on EBCT for groundwater systems. These studies and surveys are presented in Exhibit 2. Studies have shown that for most groundwater systems with low levels of contaminants, EBCTs of 7½ minutes (500 gpm per adsorber vessel) are adequate to achieve treatment objectives for most of the life of the GAC bed. In some cases of low level contamination, EBCTs as low as 5 minutes (750 gpm per adsorber vessel) have been proven to be effective.

The advantage of minimizing the EBCT is that it allows the user to minimize the amount of capital investment in treatment facilities. If water characteristics change or flow increases, additional 20,000 pound adsorber "modules" can be added to the treatment facility.

Exhibit 3 contains case studies of a variety of potable water treatment facilities that are attaining satisfactory treatment with EBCTs in the range of 5-15 minutes. The actual EBCT time selected for a site is based upon historical site and test data as shown in Exhibits 2 and 3, or pilot tests on the actual water if there is an uncertainty based on the contaminants in question.

C. Surface Loading Rate

The surface loading rate will vary depending upon the EBCT and the vessel diameter. Surface loading rates in granular activated carbon systems can be as great as 10 gpm/ft². The surface loading rate will have only a minor effect on the system's performance. Higher surface loading rates may result in slightly higher carbon usage rates, as the adsorption zone may be extended causing contaminant breakthrough to occur sooner.

Surface loading rate will affect the system pressure drop. The adsorption system is designed to take more pressure drop across the granular carbon, so that the flow is distributed across the packed bed. The downflow packed bed design is inherently a fail-safe design in that the granular media retards any channeling or short-circuiting, assuring contact with the GAC. The underdrain collection system is designed to collect the flow from the packed granular bed at a minimum of added pressure drop.

D. Backwash Design and Capability

The adsorption systems are designed to be backwashed if suspended solids in the groundwater are filtered by the GAC bed. After the GAC is installed in the adsorber vessels and prior to startup, the adsorber vessels are backwashed. This backwash accomplishes two objectives. First, small activated carbon particles, or "fines," are removed from the bed. These carbon fines may originate in the manufacture, transport, and transfer of GAC, and may cause high pressure drop or be carried into the treated water after startup. Second, the initial backwash will classify the GAC bed so that any subsequent backwash will not disrupt the bed arrangement whereby spent carbon will migrate to the bottom of the bed.

The adsorption system is designed so that the adsorber requiring backwash can be isolated from the other adsorbers and backwashed with treated water from the other adsorber(s), the distribution system, or an independent source. A backwash of 5-10 minutes at 12-15 gpm/ft² is usually sufficient to remove fines and return the system pressure drop to the design level.

E. Single State (Parallel) or Series Operation

Adsorption systems can be designed and operated as single-stage or two-stage operation. For most groundwater treatment applications, single-stage operation is recommended in order to minimize capital expense and power consumption (less pressure drop) considering the negligible savings in carbon usage. The technical references in Exhibit 2 further discuss the advantages of both approaches.

The single-stage or parallel design is dependent upon a well-designed monitoring program, and may be aided by in-bed sampling ports depending upon the adsorption system design, adsorber design, and treatment requirements.

The two-stage approach allows for complete assurance of effluent quality by changing the carbon in the first stage when contaminants are detected between stages. This design utilizes the second stage as an "insurance" stage, but will increase the treatment system capital cost by 70-80 percent, increase the power cost with little improvement in GAC usage. A second approach would be to allow the interstage contaminant level to equal the influent contaminant level to maximize GAC usage. This savings in GAC costs is offset by monitoring costs on both stages, and the improvement in GAC usage is often minor in groundwater treatment. The multiple-stage design is more prevalent in wastewater applications, where improvements in high GAC usage rates are of more benefit.

OPERATION AND MONITORING

A. Monitoring

The monitoring of an adsorption system is key to its effective performance.

In single-stage, or 12 foot diameter adsorbers, in bed sample ports are recommended to anticipate breakthrough of contaminants. The single-stage systems require sample ports, as there is no other adsorber to provide dilution effects. In 12 foot diameter adsorbers, the GAC bed is shallow, and the underdrain system collects the water across a shallow cross-section plane. This design means that the contaminants will breakthrough the system more rapidly than with 10 foot diameter beds, and it is more important to anticipate breakthrough.

In parallel operation with multiple 10 foot diameter adsorbers, either in-bed sample ports or individual adsorber monitoring may be effective. In a multiple-bed system, normal flow variations due to pressure drop, bed density, etc., will normally lead to one adsorber reaching breakthrough prior to the other units. As the contaminant may be first detected in a single adsorber effluent, the combined system effluent may remain below detection limits. At this time, all adsorbers in the parallel system may be near breakthrough, and if the effluent limit is based on detectable quantities, all units should be exchanged. If the limit is a finite concentration, more life can be provided with more frequent monitoring.

In a two-stage system, only first-stage effluent sampling is required until breakthrough. If the system is to remain on-line to optimize GAC usage, the second-stage sampling should commence, as the contaminant detected in the first-stage effluent is the least adsorbable contaminant (if there are 2 or more contaminants) in the water.

If sample taps are to be provided, they should be located in the bottom half of the bed. One sample tap with the probe extending approximately 1 foot into the GAC bed is normally sufficient. Multiple taps may provide more analysis of the mass transfer zone, which may be useful if the usage rate is expected to be substantial and the level of contamination consistent over an extended period.

B. Disinfection

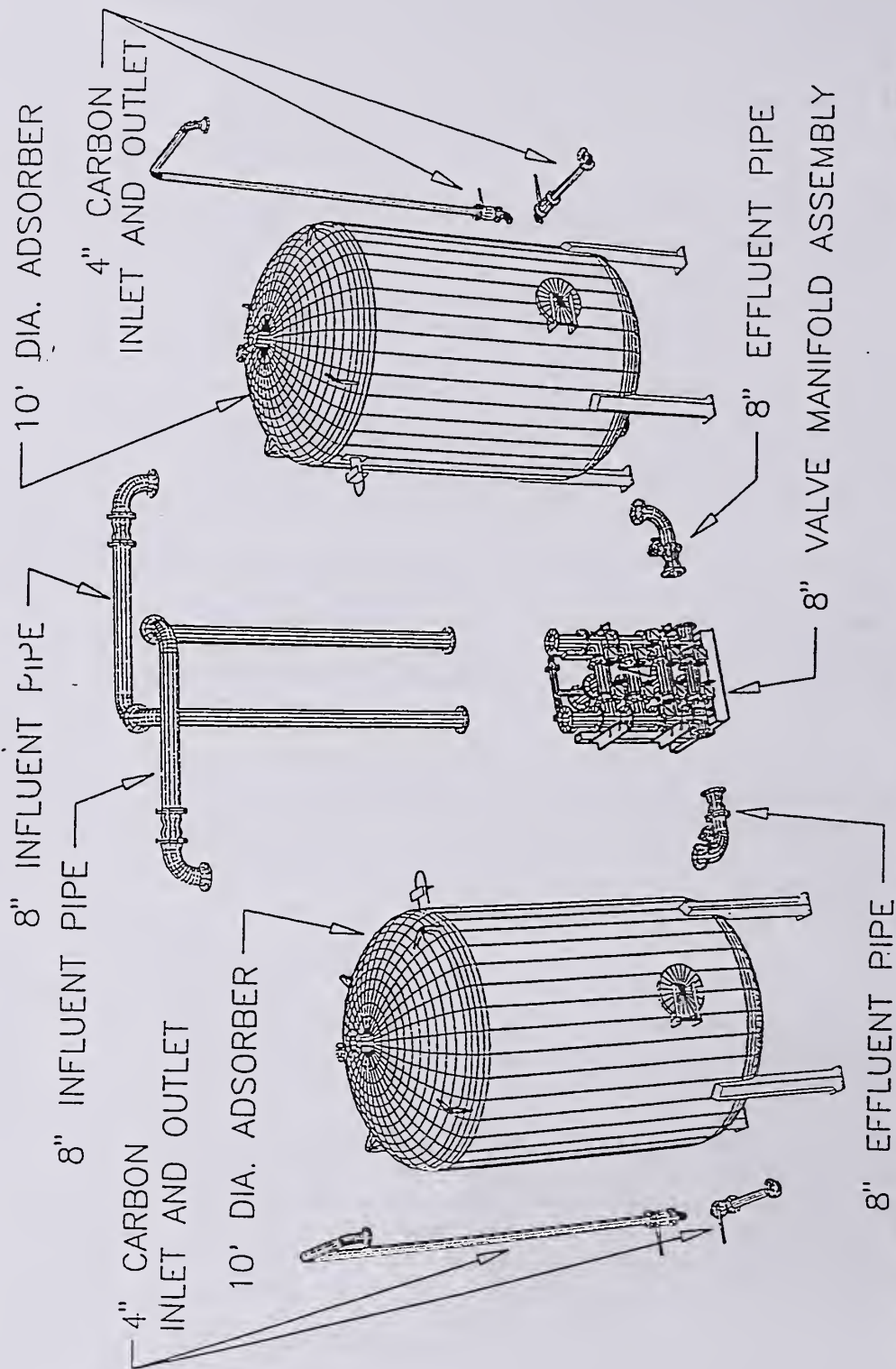
As GAC adsorbs chlorine, all disinfection should be conducted prior to placing GAC in the bed. Any subsequent disinfection procedures should include isolation of the GAC bed from the system being disinfected.

As GAC is an inert material, any disinfection procedures need not be instituted solely due to addition of GAC to the treatment system. If disinfection was conducted previously to adding carbon adsorption, it should be continued with the disinfectant added downstream of the carbon adsorption system to establish residuals in the distribution system.

C. Fail-Safe Features

The downflow fixed-bed treatment system is inherently a fail-safe treatment system. The adsorber is not affected by power outages or motor failure which might cause a component in another system to fail.

The bed will also receive flow and contaminant variations without immediately affecting treated water quality. The adsorption system can also be placed on an on-demand well system without requiring start-up procedures or other automation. The system operates without automation and/or operator attention; only periodic monitoring is required.

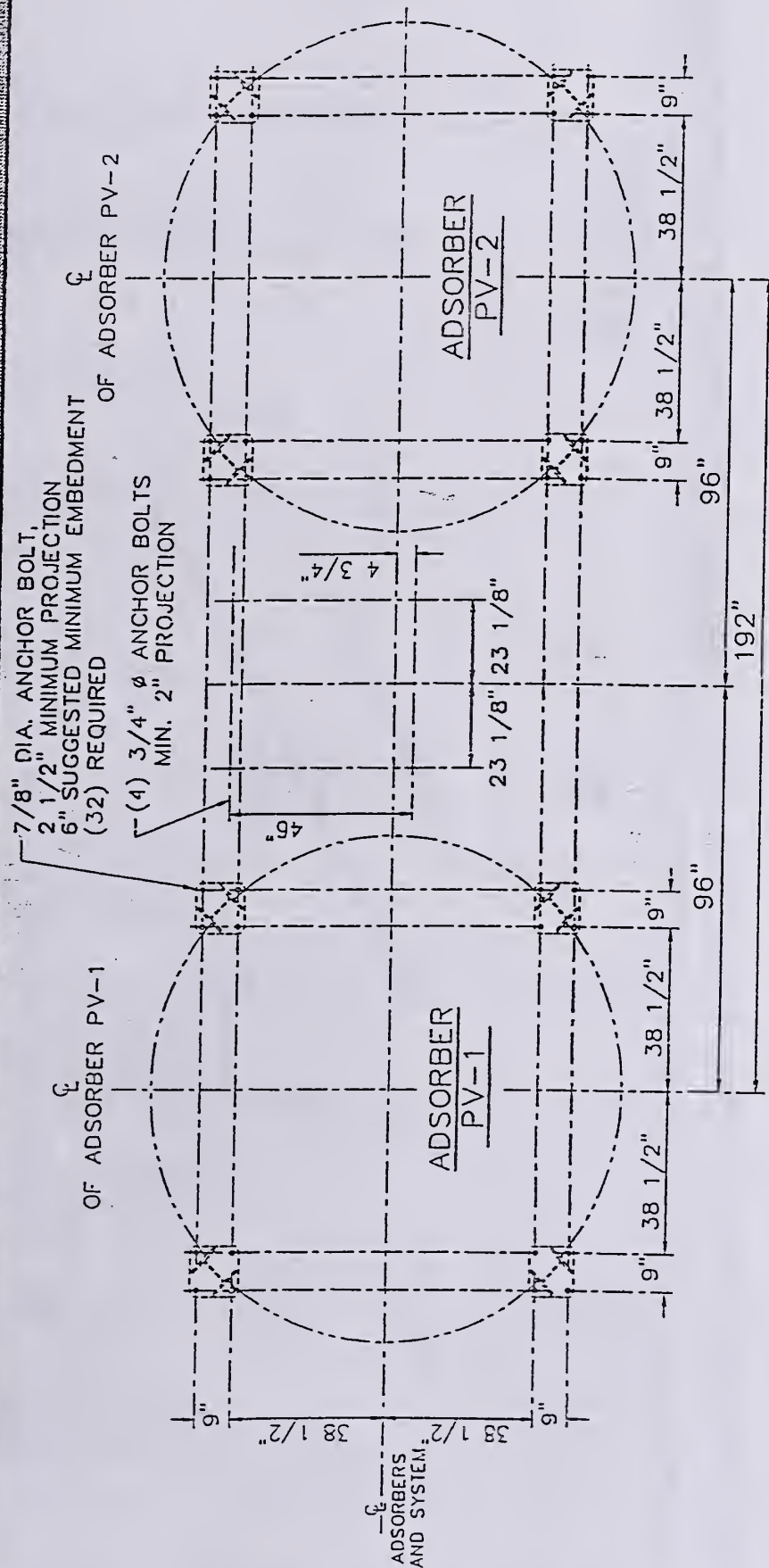


Assembly Diagram Modular 10 System

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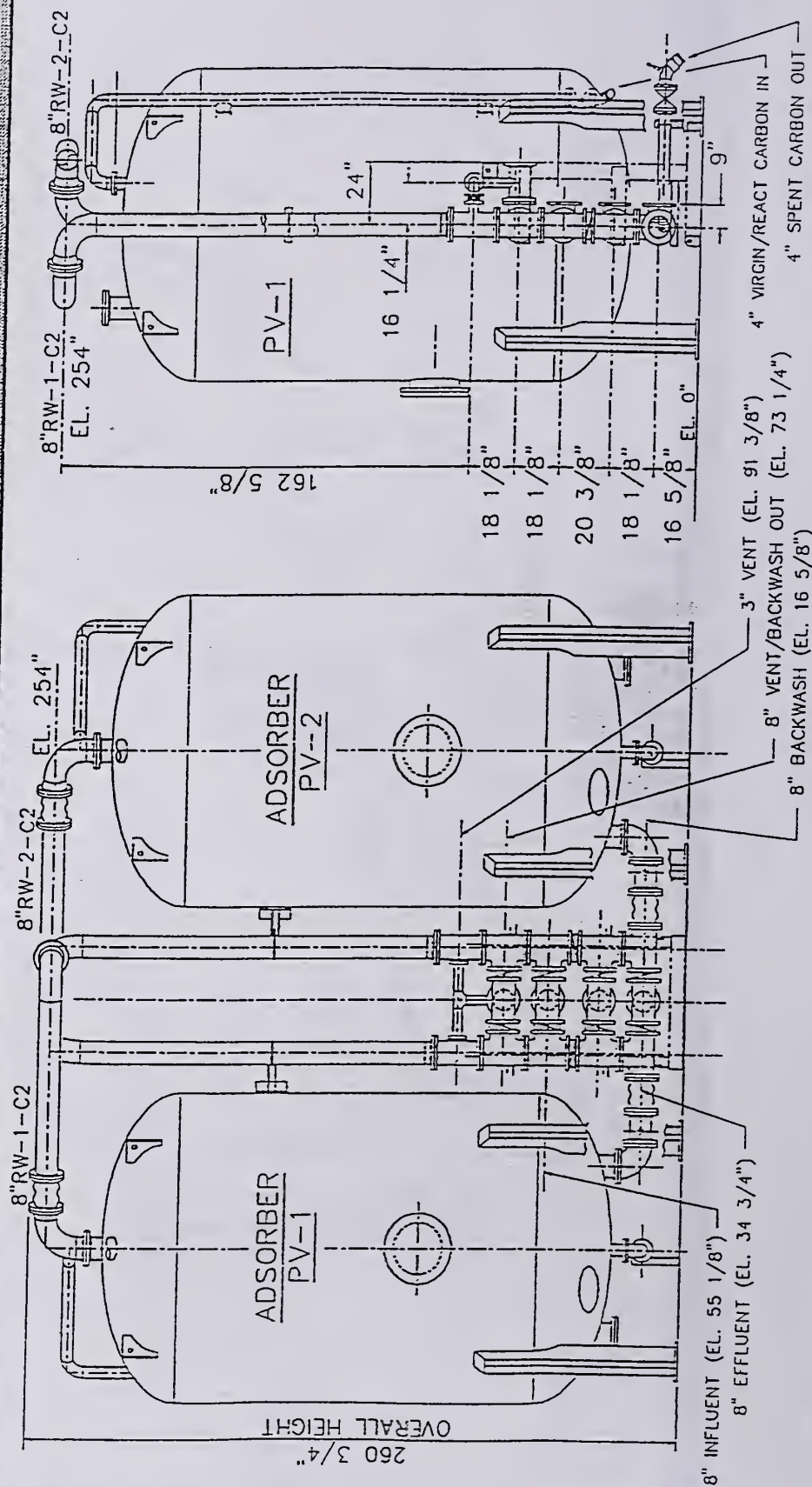
ANCHOR PATTERN SHOWN IS FOR ATTACHMENT OF VESSEL BASEPLATES TO A CONCRETE SLAB IN SEISMIC ZONE 4. THE TWO LARGE CENTER HOLES IN EACH BASEPLATE ARE FOR ATTACHMENT TO STEEL FRAMING.

Modular 10 System Footprint

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Modular 10 System Elevation View

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CALGON CARBON CORPORATION

Model 10 Modular Adsorption System

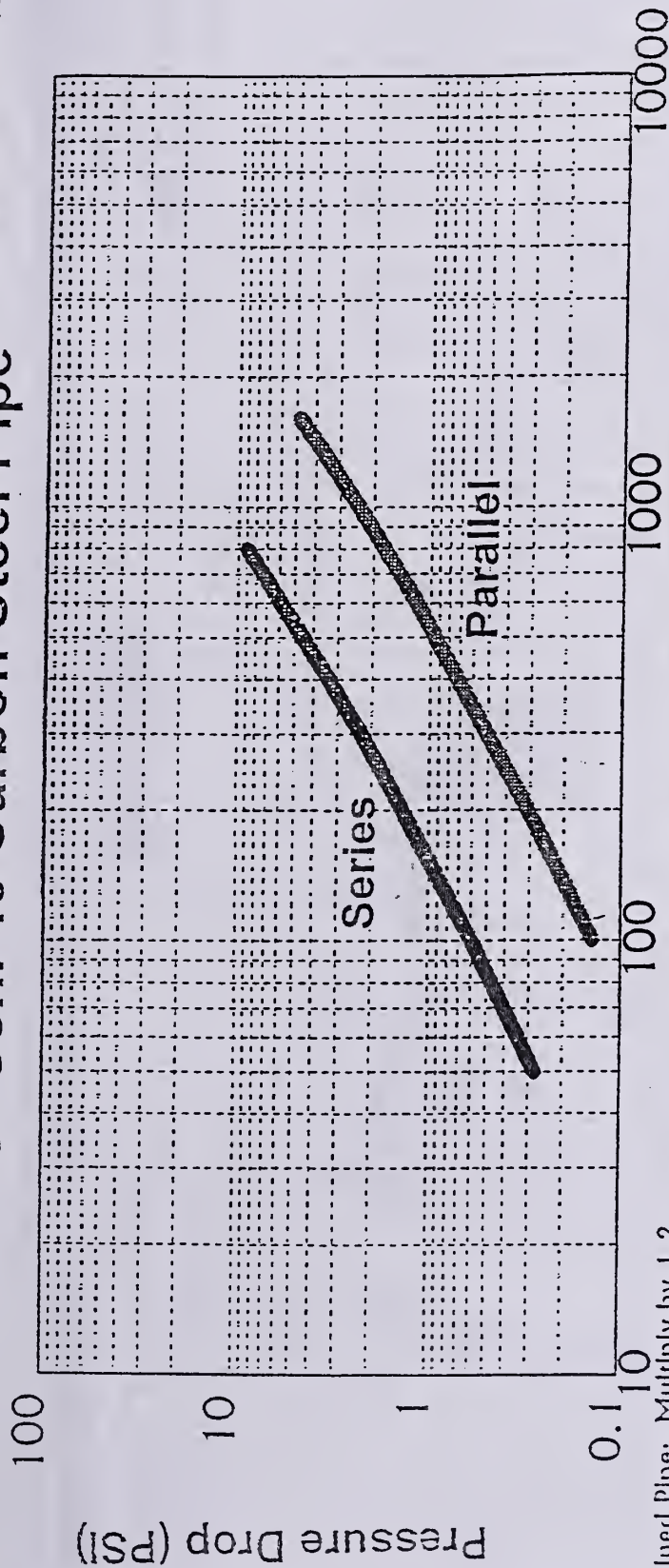
Pressure Drop

Filtrisorb 300 Carbon (55°F)

8" Sch. 40 Carbon Steel Pipe

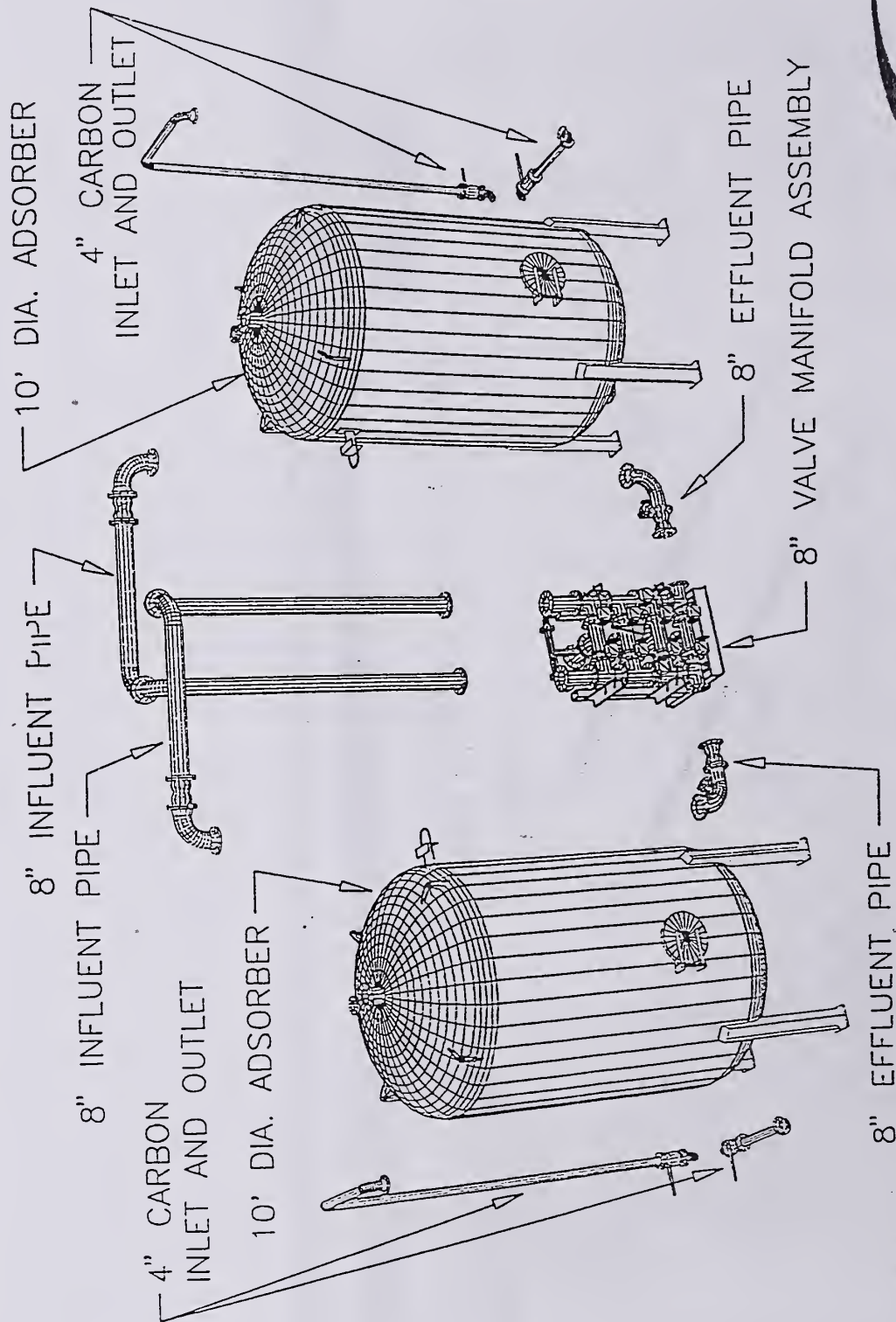
CALGON

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For Lined Pipe: Multiply by 1.2
For PVC Sch. 80 Pipe: Multiply by 1.1
2/25/94



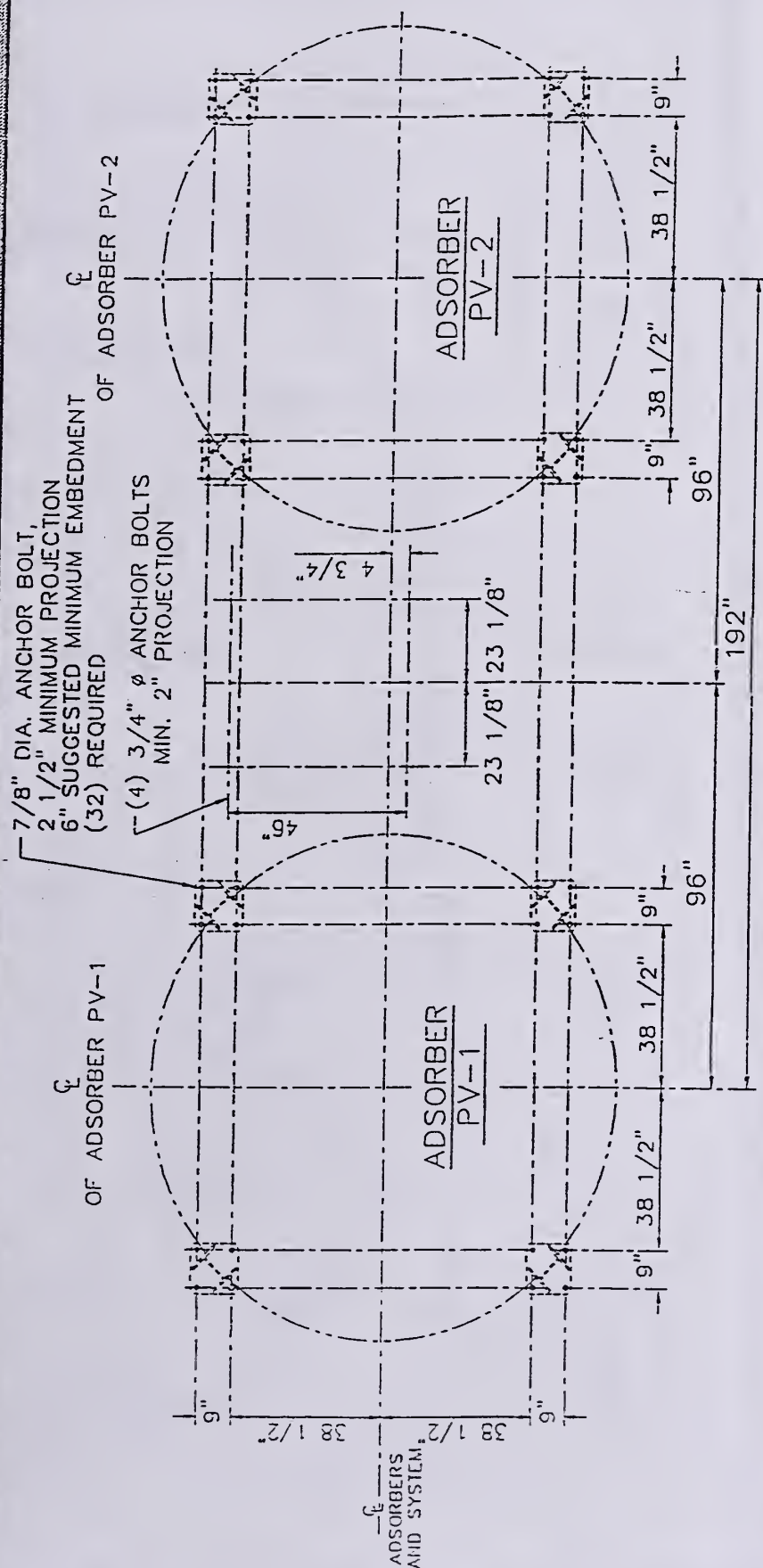


Assembly Diagram Modular 10 System

OK

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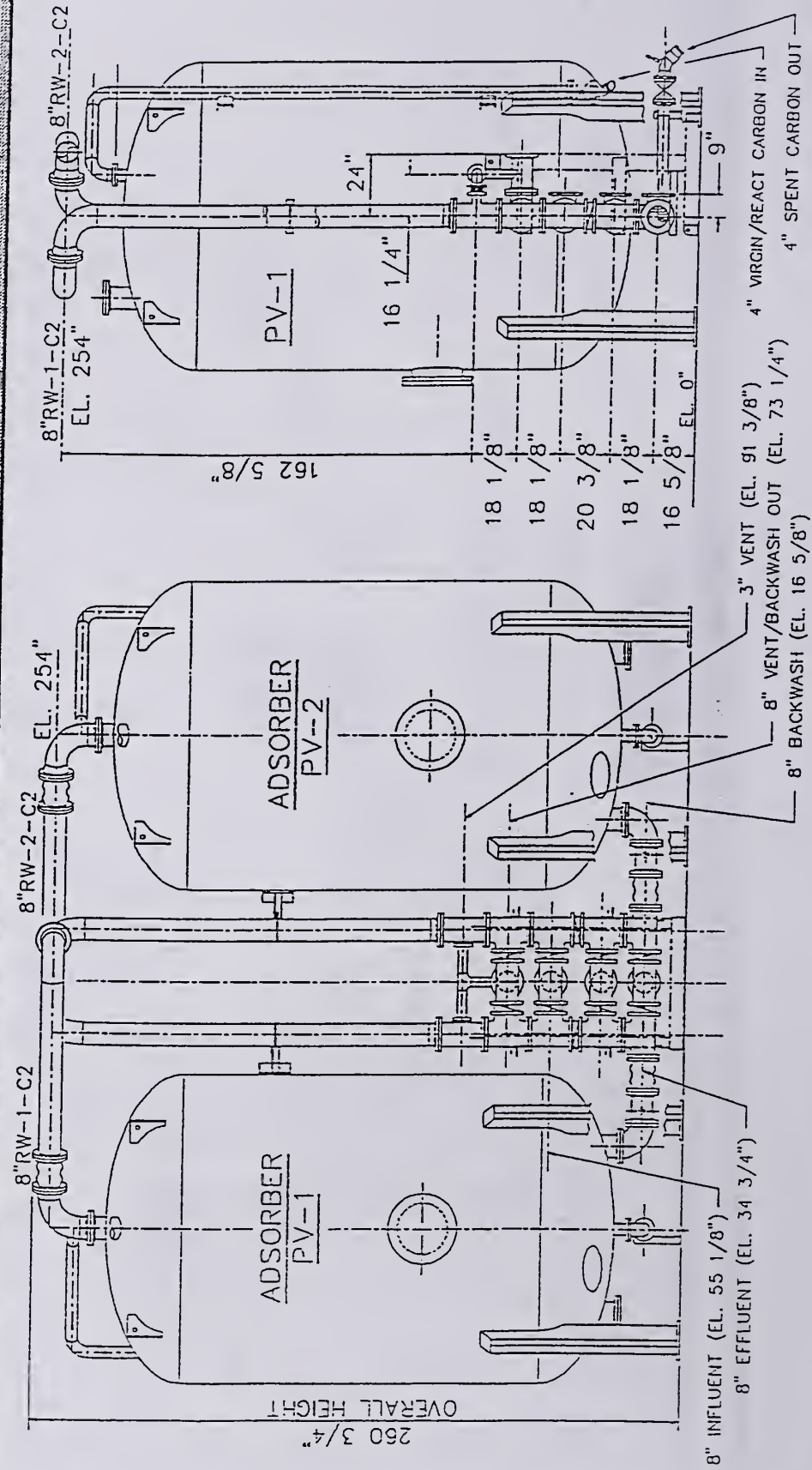
Modular 10 System

Footprint



CALGON CARBON CORPORATION





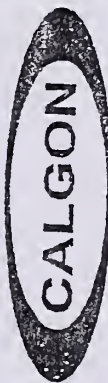
Modular 10 System

Elevation View

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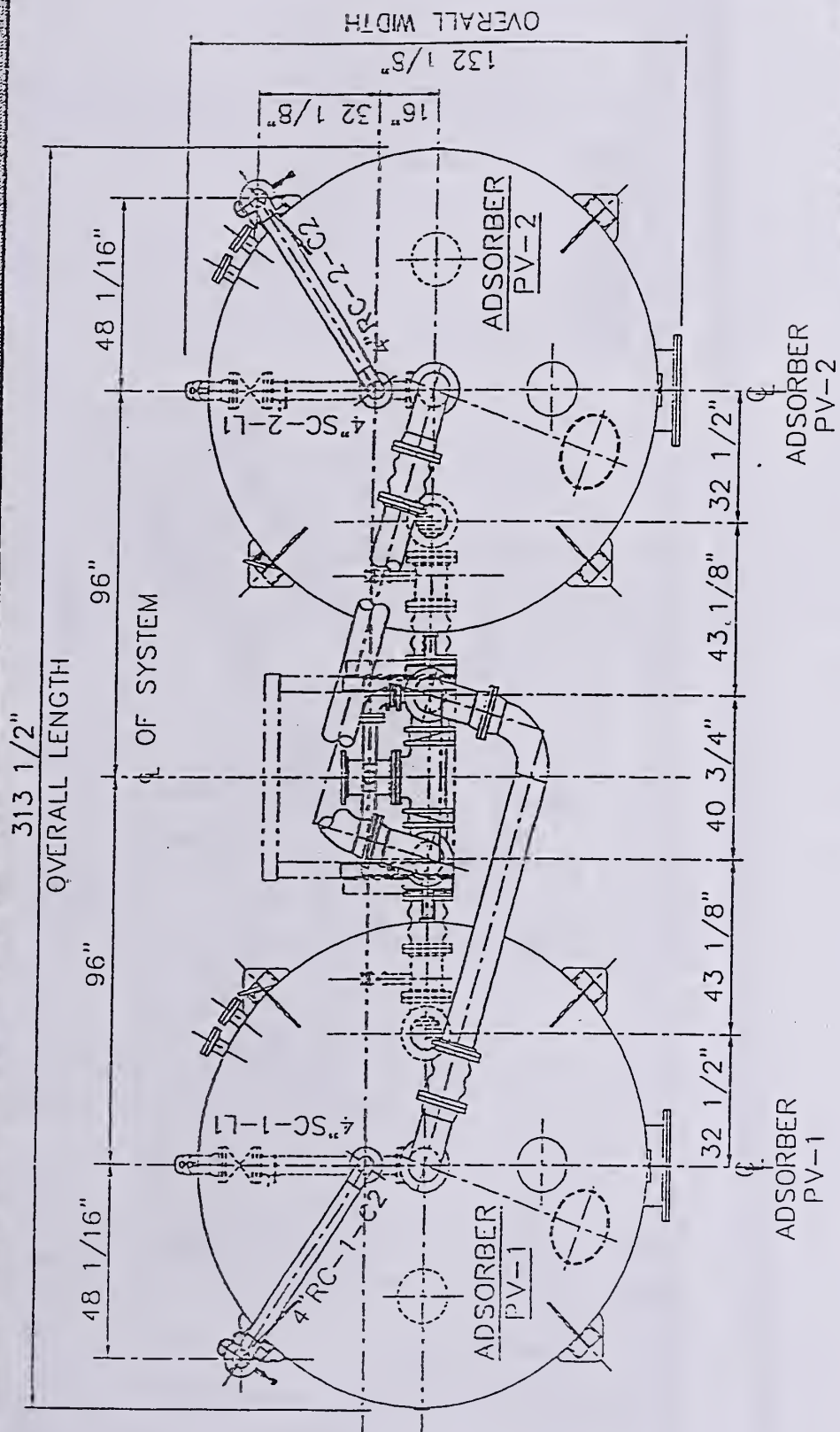


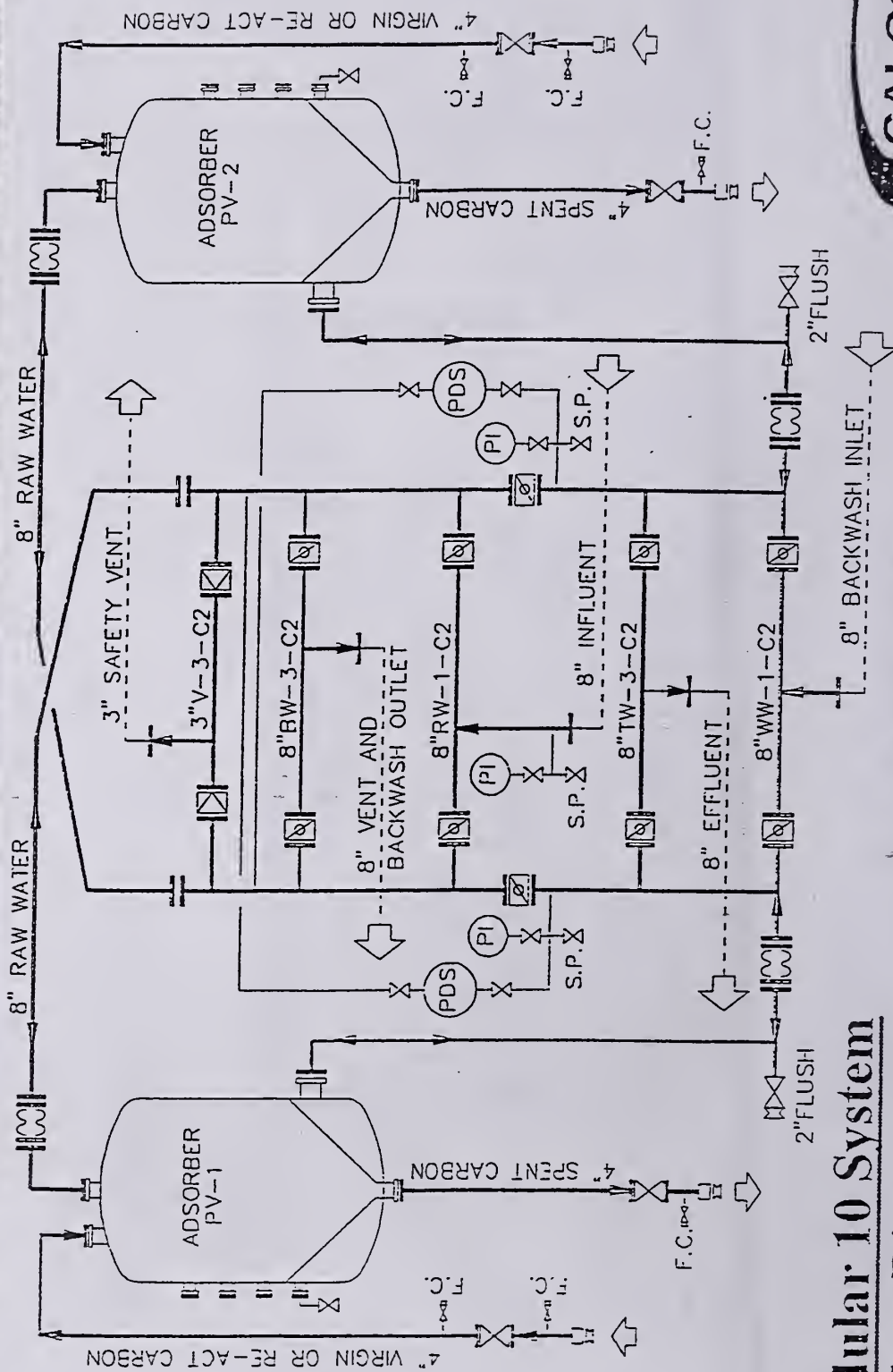
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Modular 10 System

Plan View



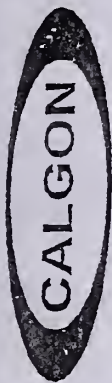


Modular 10 System Flow Diagram

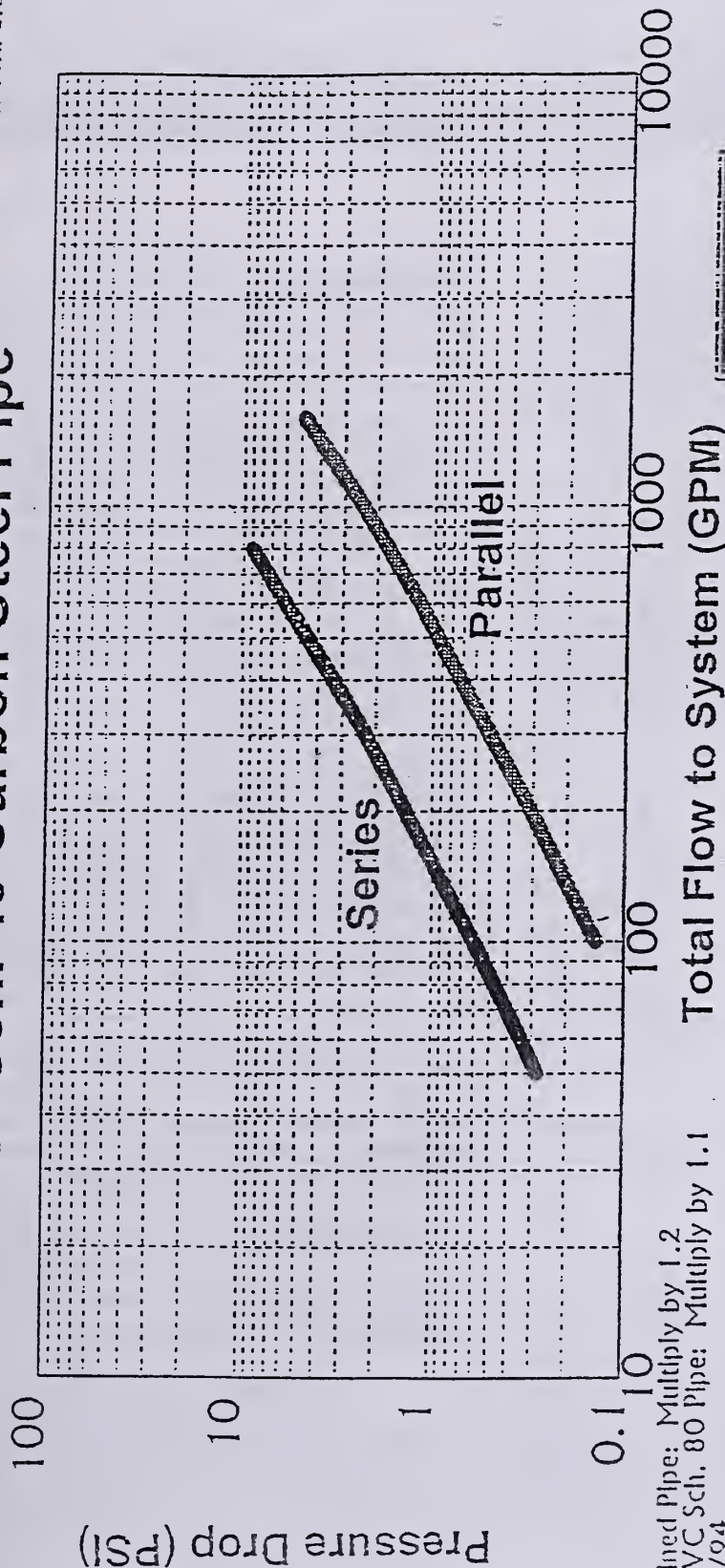


Pressure Drop

Filtrisorb 300 Carbon (55°F)
8" Sch. 40 Carbon Steel Pipe

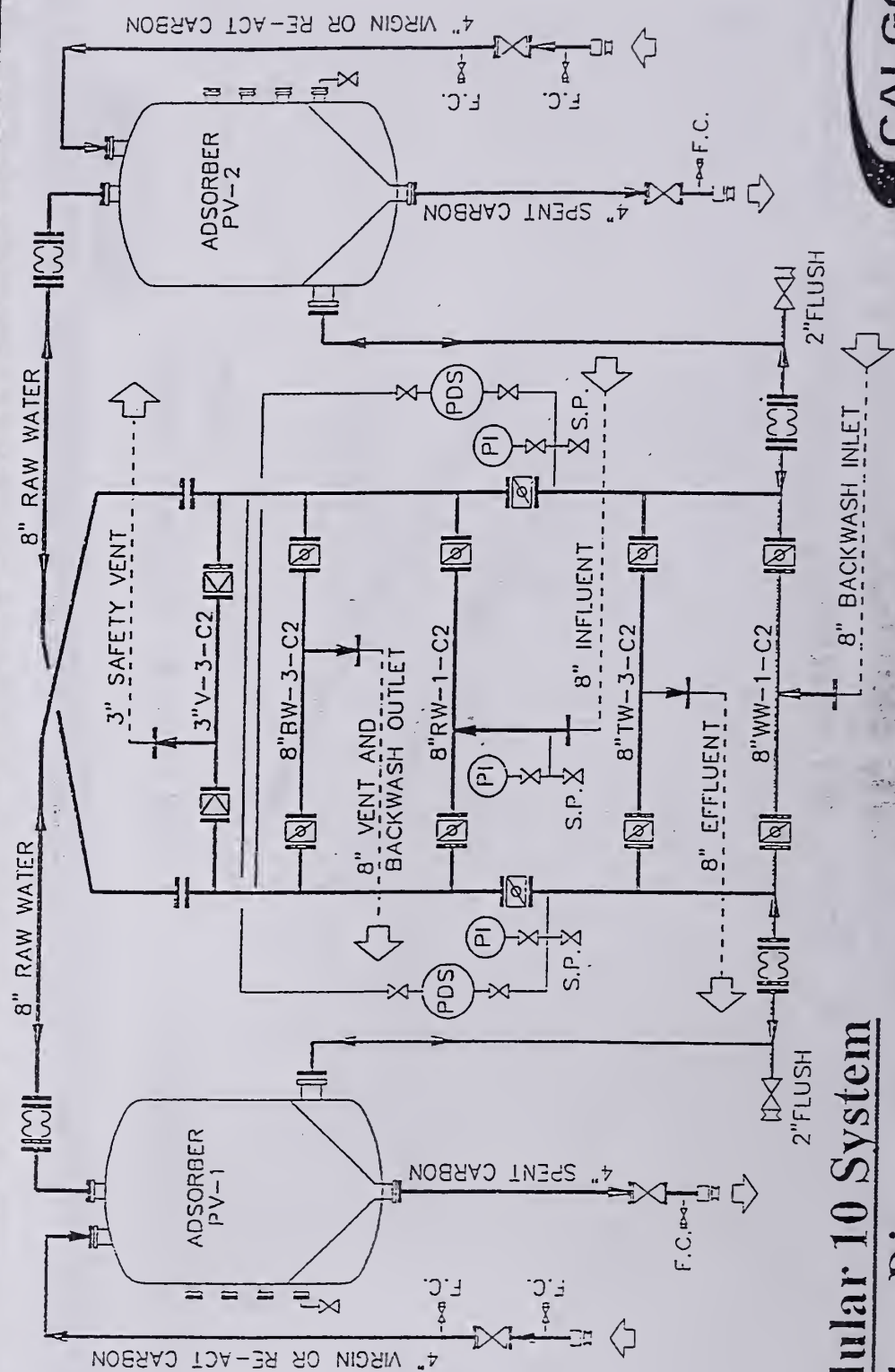


CALGON CARBON CORPORATION



For Lined Pipe: Multiply by 1.2
For PVC Sch. 80 Pipe: Multiply by 1.1
2/25/94





Modular 10 System
Flow Diagram



DESCRIPTION

The Calgon Carbon Model 10 is an adsorption system designed for the removal of dissolved organic contaminants from liquids using granular activated carbon. The modular design concept allows selection of options or alternate materials to best meet the requirements of the site and treatment application.

The Model 10 system is delivered as two adsorbers and a compact center piping network, requiring only minimal field assembly and site connections. An optional mounting skid is available to facilitate installation. The pre-engineered Model 10 design assures that all adsorption system functions can be performed with the provided equipment.

The process piping network for the Model 10 accommodates operation of the adsorbers in parallel or series (with either adsorber placed in first stage). The piping can also isolate either adsorber from the flow. This permits carbon exchange or backwash operations to be performed on one adsorber without interrupting treatment.

The unique internal cone underdrain design provides for the efficient collection of treated water and the distribution of backwash water. The internal cone also insures efficient and complete discharge of spent carbon from the adsorber. The Model 10 system is designed for use with Calgon Carbon's closed loop carbon exchange service. Using special designed trailers, spent carbon is removed from the adsorbers and returned to Calgon Carbon for reactivation. The trailers also recharge the adsorbers with fresh activated carbon.

SYSTEM SPECIFICATIONS

Carbon adsorbers:

- Carbon steel ASME code pressure vessels.
- Internal vinyl ester lining (nominal 35 mil) where GAC contacts steel, for potable water and most liquid applications.
- Polypropylene slotted nozzles for water collection and backwash distribution.

Standard adsorption system piping:

- Schedule 40 carbon steel process piping with cast iron fittings.
- Cast iron butterfly valves for process piping.
- PPL lined steel pipe for GAC discharge.
- Full bore stainless steel ball valves for GAC fill and discharge.

System external coating:

- Epoxy mastic paint system

Available options:

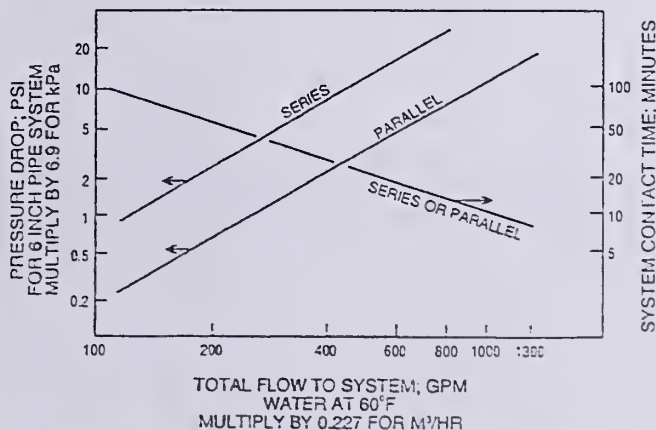
- Unifying system skid.
- In-bed water sample collection probes.



OPERATING CONDITIONS

Carbon per adsorber: 20,000 lbs. (9080 kg)
Pressure rating: 125 psig (862 kPa)
Pressure relief: Graphite rupture disk (94 psig)
Vacuum rating: 14 psig
Temperature rating: 150°F maximum (65°C)
Backwash rate: Typical 1000 gpm (30% expansion)
Carbon transfer: Air pressure slurry transfer
Utility air: 100 scfm at 30 psig
(reduce to 15 psig for trailer)

Utility water: 100 gpm at 30 psig
Freeze protection: None provided; enclosure or protection recommended





PRODUCT BULLETIN

FILTRASORB® 300 & 400

GRANULAR ACTIVATED CARBONS FOR WASTEWATER

DESCRIPTION

Filtrisorb 300 and 400 are two grades of granular activated carbon manufactured by Calgon Carbon Corporation for removal of organic pollutants from municipal or industrial wastewaters. These carbons are manufactured from select grades of bituminous coal to produce a high density, high surface area, durable granular product capable of withstanding the abrasion and dynamics associated with repeated reactivation, hydraulic transport, backwashing and mechanical handling.

APPLICATIONS

- Applying point source treatment to remove organics
- Pre-treatment to biological waste treatment systems
- Polishing effluent from biological waste treatment systems
- Recycling the treated water for replacement of groundwater or for other suitable recycling applications
- Providing total wastewater treatment

REACTIVATION

Numerous installations have demonstrated the feasibility and economy of thermal reactivation.

Exhausted granular carbon can be reactivated on your plant site in a high-temperature furnace, or it can be done by Calgon Carbon Corporation under a service agreement.

PACKAGING

55 Pound (25 kg) 5 Ply Bag
1,000 Pound (453.7 kg) Super Sack
Bulk Trucks

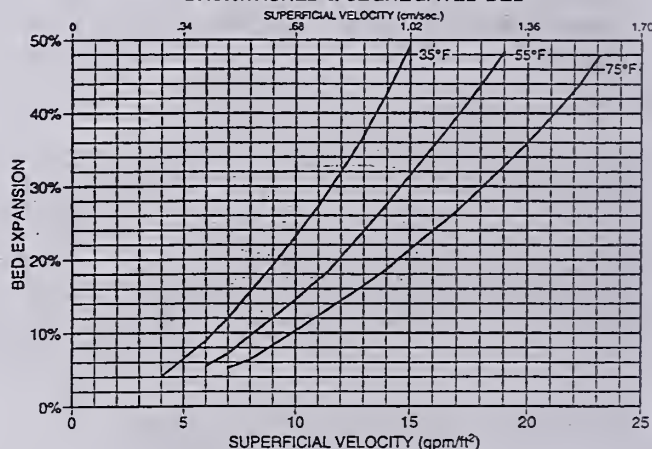
MANUFACTURING

Catlettsburg, KY
Pearlington, MS

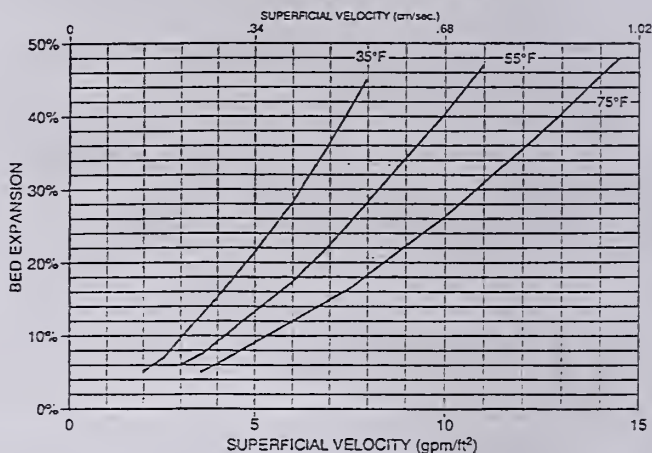
SPECIFICATIONS

	F300	F400
Iodine Number, mg/g (Min.)	900	1000
Moisture, weight % (Max. %)	2	2
Abrasion Number (Min.)	75	75
Effective Size, mm	0.8-1.0	0.55-0.75
Uniformity Coefficient (Max.)	2.1	1.9
Sieve Size, U.S. Sieve Series, weight %		
Larger than No. 8 (Max.)	15	-
Smaller than No. 30 (Max.)	4	-
Larger than No. 12 (Max.)	-	5
Smaller than No. 40 (Max.)	-	4

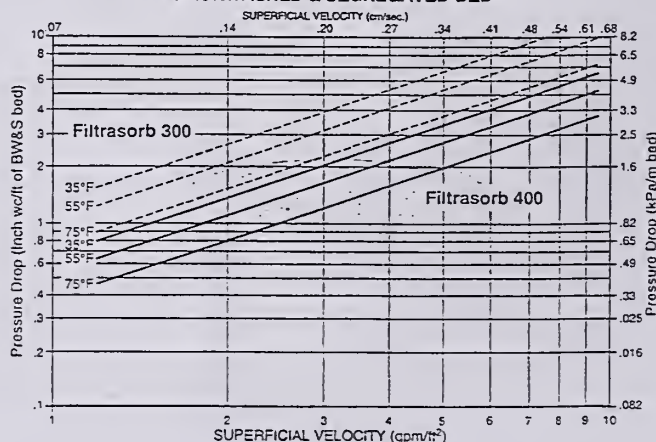
**FILTRASORB 300 - BED EXPANSION
BACKWASHED & SEGREGATED BED**



**FILTRASORB 400 - BED EXPANSION
BACKWASHED & SEGREGATED BED**



**FILTRASORB DOWNFLOW PRESSURE DROP
BACKWASHED & SEGREGATED BED**



GRANULAR ACTIVATED CARBON ADSORPTION FOR
VOC REMOVAL FROM DRINKING WATER SUPPLIES

Mark H. Stenzel
Marketing Manager

James L. Fisher
Marketing Manager

Calgon Carbon Corporation
Pittsburgh, PA 15230

INTRODUCTION

The recent amendments to the Safe Drinking Water Act (SDWA) have generated increased interest in evaluating a number of different technologies for the removal of Volatile Organic Contaminants (VOCs) from drinking water supplies. Since 1974, the EPA has generated Maximum Contaminant Levels (MCLs) for 26 contaminants, but the new amendments have called for accelerated regulation by requiring development of MCLs for 83 specific contaminants. Many of these contaminants are VOCs which have been discovered in groundwater sources for drinking water supplies. Of immediate concern are the 8 VOCs that are set for regulation in 1987, shown with their proposed MCLs in Table 1 (1).

The use of granular activated carbon (GAC) to remove organic contaminants by adsorption on the large internal surface area of the activated carbon granule has long been a proven and established technology. Over 150 public drinking water systems already have experience with GAC in the removal of taste and odor causing organic compounds in the United States and over 200 in Europe (2). Many industrial plants have also used GAC for the removal of specific organic compounds from water, wastewater and chemical products. Recently, GAC has been used to remove specific VOCs from groundwater or contaminated water resulting from accidental spills (3).

The success of GAC in removing organic contaminants from water has resulted in the amendment to the SDWA establishing GAC as the "yardstick" by which other treatment technologies are to be evaluated in the control of synthetic organic chemicals (4). Other treatment techniques must be at least as effective as GAC in order to be considered viable. Although often perceived as an expensive treatment technology, GAC can often be the most cost-effective solution to the problem at hand. What is needed is a reliable method to evaluate the applicability of adsorption and to estimate the cost to the water system operator.

This paper will present a methodology by which GAC can be evaluated, starting with isotherms for preliminary evaluation and continuing on to parameters for system design. The design of the GAC system will provide capital expenditure guidelines, while the evaluation procedure



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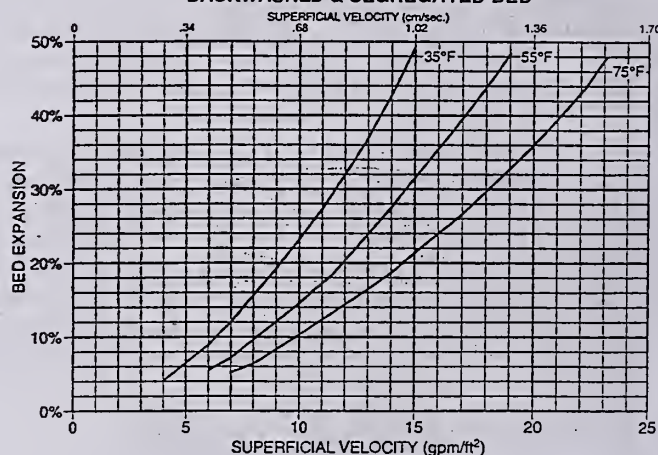
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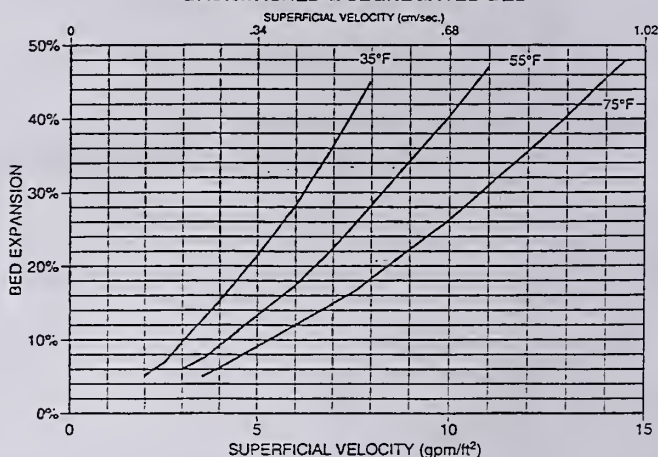
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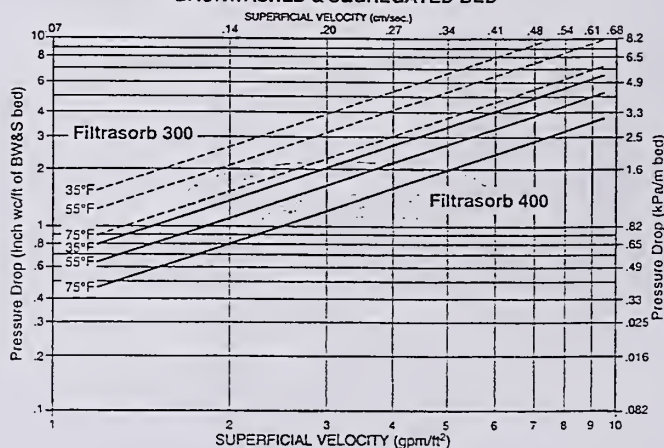
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This paper will present a methodology by which GAC can be evaluated, starting with isotherms for preliminary evaluation and continuing on to parameters for system design. The design of the GAC system will provide capital expenditure guidelines, while the evaluation procedure

Figure 2 shows the results of isotherms for seven of the VOCs due for regulation in 1987. The eighth VOC, vinyl chloride, is normally a gas at ambient temperature, and has a very low capacity on GAC in liquid phase adsorption. Investigations into the removal of vinyl chloride by activated carbon have reported poor capacities. However, vinyl chloride removal by aeration has produced good removal efficiencies (7). The isotherm results for p-dichlorobenzene are from earlier test results using less agitation time, but p-dichlorobenzene is well adsorbed by activated carbon and the results are consistent with recent tests.

Figure 3 has grouped the remaining chlorinated and brominated aliphatic solvents and Figure 4 the aromatic and chlorinated aromatic solvents. The isotherms point out characteristics useful for considering adsorption of other compounds; i.e., that the capacity of activated carbon for the contaminant increases with concentration, molecular weight and decreasing solubility of the contaminant.

Isotherms are useful in identifying whether a compound is amenable to adsorption by activated carbon. The test indicates the theoretical capacity for these contaminants by GAC, which as will be shown later, allows the development of estimates of carbon usage rates for cases where a single contaminant predominates. Care must be taken in using these single component isotherms when the contamination involves a mixture of adsorbable compounds. Although these isotherms might allow for preliminary estimates of activated carbon usage rates, additional testing would be warranted to establish more reliable carbon usage rates. Finally, background organic contaminants, usually more prevalent in surface water than groundwater, may cause reduced capacity. Isotherms performed on a specific water according to these procedures would provide for good comparison to these single component isotherms and a basis for estimating GAC usage rates.

After a column study is performed or actual operating data is obtained, isotherms are useful in evaluating effects of concentration or contaminant change. A relationship can be established between the actual usage rate and the equilibrium data of the isotherm, and changes in usage rate can be predicted using the isotherms as reference points.

ADVANCED EVALUATION: ACCELERATED COLUMN TESTING

The effect of short contact times experienced in actual operation and the accurate prediction of activated carbon usage rates is normally obtained in the scaled column study. The accepted test method for the column study has been to use the GAC in columns sized from 1 to 4 inches in diameter, and with selection of surface loading rates and media depth, obtain the desired empty bed contact times in single or multiple columns. The low usage rates expected

situations. The first site shows the effect of higher contaminant levels of a well adsorbed VOC. With higher levels of trichloroethylene (TCE) and slightly greater than 15 minutes contact time, the ACT predicts a 68% attainment of the equilibrium isotherm data. This result indicates that in the adsorption process, the higher concentration contaminant acts as a greater driving force towards equilibrium capacity.

The second site investigated shows the influence of background organic contaminants on the adsorption of chlorinated solvents. A municipal drinking water containing 135 ppb of chloroform that also contained 6 ppm background organic contamination measured as TOC was tested. The ACT indicated that the presence of this organic background resulted in only 37% of the theoretical capacity being achieved. This capacity is approximately 20% less than the capacity achieved in the municipal drinking water sample shown on Table 2.

The third site in this set shows the effects of a mixture of VOCs; 1,1,1 trichloroethane (TCA) and TCE. As shown in the isotherm data in Figure 2, the TCA is not adsorbed as strongly, so it is expected to break through first. The column study did indicate that the TCA was detected first in the effluent, and the capacity of carbon for TCA was only 34.3% of its equilibrium value. Another way of looking at this mix is that at an equilibrium capacity of 3.5 mg/gm and 55 ppb of TCA, the theoretical usage rate would be 0.13 lbs. GAC per thousand gallons. This usage rate can be added to a usage rate of 0.06 lbs. GAC/1000 gallons for TCE (24 mg/gm at 165 ppb) for a total usage rate of 0.19 lbs. GAC/1000 gallons for both contaminants. The actual usage rate is approximately 58% greater than the theoretical, indicating a working capacity that realizes approximately 63% of the equilibrium capacity.

In considering these ACT studies on VOC removal, it can be concluded that for low level VOC contamination in waters containing low background TOC, operating activated carbon adsorption systems can achieve 45-55% of the theoretical isotherm capacity. When the chemistry becomes more complex, with background TOC or the presence of a mixture of contaminants, a simple rapid mini-column technique can be conducted to explore these additional effects.

ADSORPTION SYSTEM DESIGN AND ECONOMICS

Based upon the evaluation procedure discussed above, the investigator can proceed with preliminary system design and establish the economics for activated carbon treatment. It was shown earlier that for waters with one or two VOCs present at low levels - 200 ppb or less, contact times of 12 to 15 minutes are acceptable. Also, for these conditions, and especially if only a single VOC is present, the mass transfer zone is sufficiently short that a single stage adsorption system can usually achieve optimum economic utilization of the activated carbon. The use of single stage systems rather than multiple stages

Estimated Capacity: 12.5 mg TCE/gm GAC
Estimated GAC Usage: 0.12 lbs./1000 gallons
Estimated Annual GAC Usage: 40,000 lbs.

To predict the operating cost, an estimate is made for the installation of the adsorption system as shown in Table 4, resulting in a total installed capital expenditure of approximately \$250,000. In some geographical areas, freeze protection such as insulation with heat tracing, or a building, may also be necessary.

Finally, the annualized operating cost for the adsorption system can be estimated by amortization of the capital expenditure and addition of the expenses as shown in Table 5. The unit cost for the treatment system under consideration can therefore be estimated to be 27 cents for each 1000 gallons treated. This figure is consistent with a value of 34 cents per 1000 gallons estimated by the EPA for systems below 1 mgd and for 99% removal of TCE up to 500 ppb (9).

CONCLUSION

The recent interest in technologies for treatment of waters contaminated with low levels of VOCs has increased the need for reliable data bases to be used for preliminary evaluation. This need is especially critical in the evaluation of activated carbon adsorption, which is regarded as the basis by which other technologies are measured.

The adsorption isotherm is the basic evaluative tool for activated carbon adsorption, and can be an effective predictor for activated carbon usage rates when combined with reliable dynamic studies. For the isotherms presented in this paper, care was taken to minimize analytical errors and assure equilibrium conditions. As a result, this series of isotherms can be compared to each other and used as a reliable point of reference for column studies. Finally, rapid mini-column tests similar to the Accelerated Column Test can be used to effectively model full scale systems.

Results discussed here indicate that for groundwaters contaminated with essentially a single VOC at low levels with little background organic contaminants, 45-55% of the equilibrium capacity can be obtained using contact times of 12 to 15 minutes. The short mass transfer zones also indicate that single stage adsorbers can be employed to minimize capital expenditures.

The methodology exists then, to properly evaluate activated carbon treatment for both performance operation and costs. This procedure will be helpful as a point of reference to evaluate other treatment technologies and as a planning technique for the employment of activated carbon adsorption.

FIGURE 1
ACTIVATED CARBON
ISOTHERM REPORT

SAMPLE VOLUME	<u>137 ml</u>
TEMPERATURE	<u>AMBIENT</u>
AGITATION TIME	<u>20 hrs.</u>
CARBON	<u>FILTRASORB 300</u>
CONTAMINANT	<u> </u>

GRAMS CARBON	REMAINING		ADSORBED mg	ADSORPTIVE CAPACITY mg/gm
	mg/l	mg		
Control	400		--	--
0.05				
0.25	(meas.)		(by difference)	(calculated)
0.5				
1.0				
2.5				
5.0				
10.0				
20.0				

FIGURE 3
ACTIVATED CARBON ADSORPTION ISOTHERMS
CHLORINATED SOLVENTS

- | | |
|------------------------------|------------------------|
| (1) Tetrachloroethylene | (4) Chloroform |
| (2) Trichloroethylene | (5) 1,2 Dichloroethane |
| (3) Cis 1,2 Dichloroethylene | (6) Methylene Chloride |

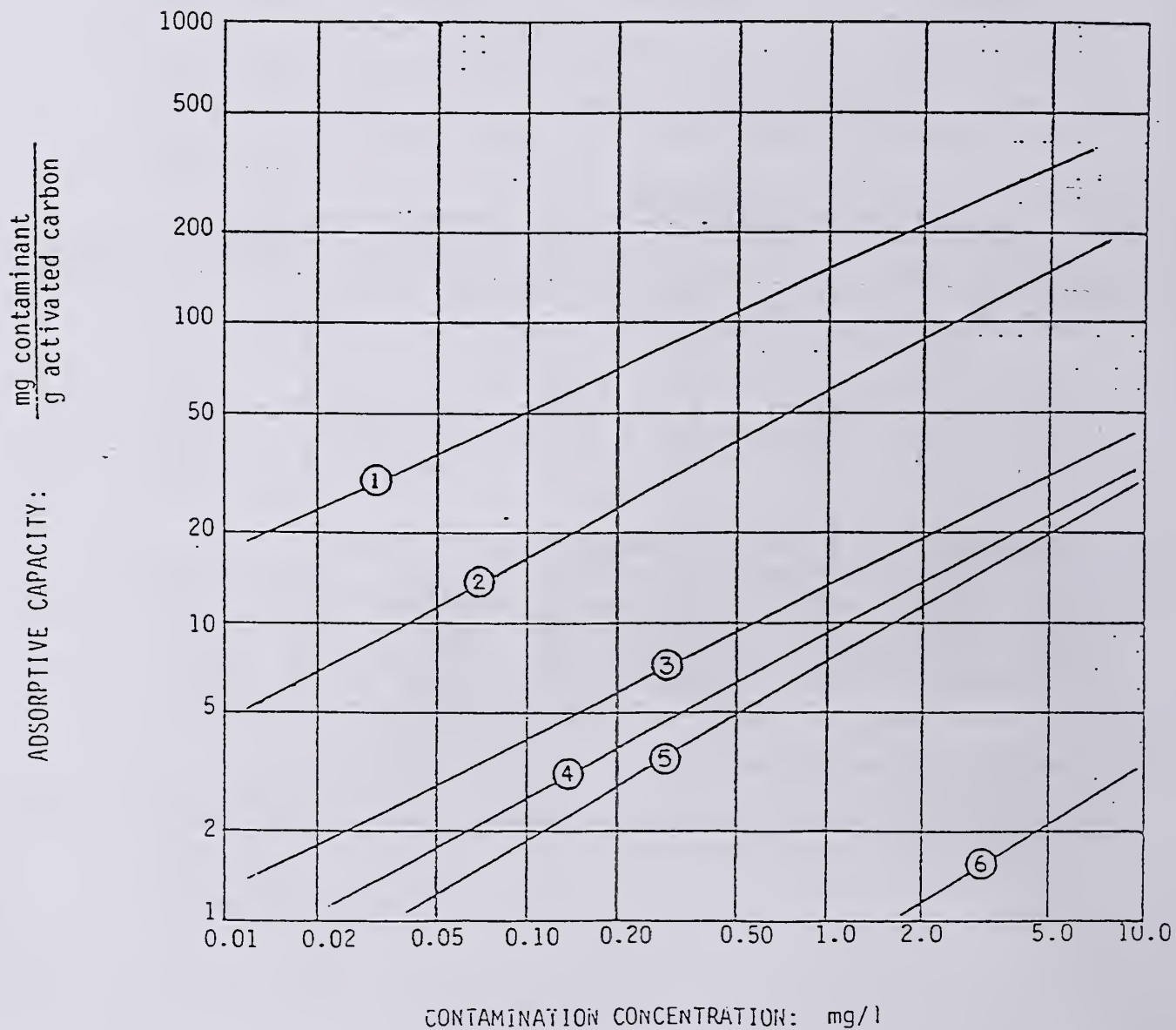


TABLE 1
Proposed VOC Regulations

VOC	Maximum Contaminant Level (MCL); ug/l
Vinyl Chloride	2
Benzene	5
Carbon Tetrachloride	5
1,2 - Dichloroethane	5
Trichloroethylene	5
1,1 - Dichloroethylene	7
p-Dichlorobenzene	75
1,1,1 - Trichloroethane	200

TABLE 3
ACCELERATED COLUMN TEST STUDIES
SELECTED VOC CONTAMINATION CASES

SITE	CONTAMINANT	INDUSTRIAL, GROUNDWATER	MUNICIPAL, DRINKING WATER	GROUNDWATER		
				SINGLE COMPONENT	TWO COMPONENT	
		TRICHLORO-ETHYLENE	CHLOROFORM	1,1,1 TRICHLOROETHANE	1,1,2,2-TETRACHLOROETHANE	TRICHLOROETHYLENE
CONCENTRATION, ppb EFFLUENT OBJECTIVE, ppb CONTACT TIME, minutes GAC USAGE RATE pounds/1000 gallons REALIZED CAPACITY mg/gm ISOTHERM (EQUILIBRIUM)		3300	1.35	55	55	165
		1	1	1	--	--
		18	20	25	--	--
		0.45	1.1	0.3	--	--
		61	1.0	1.2	--	--
		90	2.7	3.5	3.5	24.0
USAGE RATE FROM ISOTHERM CAPACITY pounds/1000 gals.		--	--	--	0.13	0.06
					(TOTAL = 0.19)	
PERCENT OF EQUILIBRIUM CAPACITY REALIZED		67.8%	37.0%	34.3%	63.3%	
	BACKGROUND CONTAMINATION	--	6 ppm TOC	165 ppb TCE	---	



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CERTIFICATE OF COMPLIANCE

CERTIFICATE NUMBER: 050793 - MH17374

ISSUE DATE: 07 May 1993

Issued to: Calgon Carbon Corporation
P.O. Box 717
Pittsburgh, PA 15230-0717

Report Reference: MH17374, 13 October 1992

This is to Certify that
representative samples of: Granular Activated Carbon

Have been investigated by Underwriters Laboratories Inc. in accordance with the Standard(s)
indicated on this Certificate.

Standard(s) for Safety: ANSI/NSF Standard 61, Drinking Water System
Components-Health Effects

Additional Information:

Only those products bearing the UL Classification Marking should be considered as being
covered by UL's Classification and Follow-Up Service.

The UL Classification Marking includes: the name "Underwriters Laboratories Inc."; the word "Classified"; a control
number (may be alphanumeric) assigned by UL; a statement to indicate the extent of UL's evaluation of the product;
and, the product category name (product identity) as indicated in the appropriate UL Directory.

LOOK FOR THE UL CLASSIFICATION MARKING ON THE PRODUCT

Engineer: *Gurie Korfuss*
Underwriters Laboratories Inc.

Review Engineer: *Ken Peng Sir*
Underwriters Laboratories Inc.

ANSI/NSF STANDARD 61
LISTING OF CERTIFIED DRINKING WATER SYSTEM COMPONENTS - HEALTH EFFECTS

[131]

CALGON CARBON CORPORATION
PO BOX 717
PITTSBURGH, PA 15230-0717

Plant At: CATLETTSBURG, KY

Process Media

Trade Designation	Size	Water Contact Temp	Water Contact Material
<i>Powdered Activated Carbon</i>			
Powder Activated Carbon*** +	NA	CLD 23	PAC
<i>Granular Activated Carbon</i>			
Granular Activated Carbon* **	NA	CLD 23	GAC
<i>Acid - Washed Granular Activated Carbon</i>			
Acid-Washed Granular Activated Carbon* ****	NA	CLD 23	GAC

Certified for water treatment plant applications only.
 This product has not been evaluated for point of use applications.

- * Product was evaluated using a conditioning and backwashing procedure simulating a typical water treatment plant installation.
- ** Any granular activated carbon product from this site, with the exception of Cane Cal and Canesorb, is NSF Listed to Standard 61 whether or not it bears the NSF Mark.
- *** Any powdered activated carbon product from this site is NSF Listed to Standard 61 whether or not it bears the NSF Mark.
- + The product is certified with a maximum use level of 250 mg/L.
- **** Any acid washed granular activated carbon product from this site is NSF Listed to Standard 61 whether or not it bears the NSF Mark.

Plant At: PITTSBURGH, PA

Process Media

Trade Designation	Size	Water Contact Temp	Water Contact Material
<i>Powdered Activated Carbon</i>			
Powder Activated Carbon	NA	CLD 23	PAC

Certified for water treatment plant applications only.
 This product has not been evaluated for point of use applications.

This product is certified with a maximum use level of 250 mg/L.
 Any powdered activated carbon product from this site is NSF Listed to Standard 61 whether or not it bears the NSF Mark.

Plant At: PITTSBURGH, PA

Process Media

Trade Designation	Size	Water Contact Temp	Water Contact Material
<i>Powdered Activated Carbon</i>			
Powder Activated Carbon*** +	NA	CLD 23	PAC
<i>Granular Activated Carbon</i>			
Granular Activated Carbon* **	NA	CLD 23	GAC

GRANULAR ACTIVATED CARBON

A. GRANULAR ACTIVATED CARBON INVENTORY AND POINT OF MANUFACTURE

Calgon Carbon Corporation is the United States' largest producer of granular activated carbon (GAC). The current capacity of the Corporation is 166,000,000 pounds on an annual basis. The Corporation is also in the process of building a new plant to produce an additional 30,000,000 pounds of activated carbon at a U.S. Gulf Coast location. This new plant is expected to be operational in late 1991.

A single product line at our Catlettsburg, Kentucky, facility is capable of producing 80,000 lbs./day of Filtrasorb 300 granular activated carbon, supply of adequate product is effectively assured.

Point of manufacture for this project will be the Catlettsburg, Kentucky, facility. Actual inventory of F-300 is dependent 5 upon factors including current production and orders, but supply of this project would be a dedicated production run, testing as specified and storage/shipment to site.

B. GRANULAR ACTIVATED CARBON DELIVERY AND TRANSFER

CALGON Carbon Corporation maintains a fleet of granular activated carbon delivery trailers dedicated for transport of potable grade granular activated carbon. The trailers are identical to those described on the attached drawing. The fleet capabilities of Calgon Carbon are as follows:

Dedicated Trailers for Virgin Grade GAC Delivery	4
Tractors for Trailer Transport	16
Trained Drivers for Delivery and GAC Transfer	32

The GAC will be transported to the designated site in the FDA approved food grade trailer with a Plasite 4006 lining. One trailer of this type has the ability to transport and transfer the necessary 20,000 pound shipments of Filtrasorb 300 GAC.

The trailer driver will connect the necessary hoses and operate all the valves on the trailer. A plant operator should be available to operate the valves on the adsorber skid. The driver will monitor the sequence of operations to ensure the correct procedures are being followed as described in the Exhibit.

Upon completion of the GAC transfer, the driver will disconnect the hoses and close the valves on the trailer. The plant operator will close the valves in the vent and GAC fill lines on the adsorber. When these operations are completed, the adsorber can be placed in service.

CALGON CARBON'S REACTIVATION CAPABILITIES

Calgon Carbon Corporation is the largest manufacturer and reactivator of granular activated carbon in the United States. The company owns two 80,000 lbs. per day carbon reactivation facilities in the U.S.-one at Neville Island, PA, and one at Catlettsburg, KY.. These facilities are the most sophisticated in the world dedicated to the safe and effective handling, storing, and reactivation of spent activated carbon. In fact, the Neville Island facility was the first carbon reactivation facility in the U.S. to receive a final RCRA Part B Permit to handle and store RCRA manifested spent carbons (1988). The Catlettsburg facility received its final Part B Permit in 1990 and is functionally similar to Neville Island, PA.

This report will briefly describe the Calgon Carbon reactivation program and facilities. It will explain why Calgon Carbon is uniquely prepared to provide users assurances that their spent carbon reactivation needs will be legally, safely and effectively accomplished. It will detail how Calgon Carbon helps users eliminate on-going liability for hazardous organic compounds.

Step 1 - Proper Spent Carbon Reactivation Evaluation

Calgon Carbon's process to insure that a spent carbon be legally, and safely reactivated begins long before the carbon is returned to Calgon's facilities. First, relevant data must be obtained and a reactivation acceptance test conducted. With the cooperation of the prospective customer, Calgon Carbon Corporation obtains the following information:

- a. The Adsorbate Profile Document
- b. A Certification Statement regarding "Exemption" Compounds
- c. A Certification statement on RCRA Classification
- d. Formal Carbon Acceptance Request

Additionally, Calgon Carbon's Research Department obtains and evaluates samples of spent carbons from all prospective customers in our laboratory prior to acceptance for reactivation. In the laboratory reaction study, the spent carbon is thoroughly analyzed to see if there could be any storage problems. It is then laboratory prior to acceptance for reactivation. In the laboratory reactivation study, the spent carbon is thoroughly analyzed to see if there could be any storage problems. It is then laboratory reactivated to evaluate (1) whether there would be any reactivation emission problems, and (2) if the carbon can be reactivated to acceptable quality.

When all the above data is obtained and the laboratory study

completed, a Carbon Reactivation Acceptance Committee within Calgon Carbon meets to review the data and make its recommendations and/or decisions regarding carbon acceptance. When necessary, Calgon Carbon will consult with local, state or federal agencies to insure their concurrence on any recommended decision. Calgon Carbon can handle most spent carbons, but will not accept spent carbons that contain PCBs, dioxin or 1,2 DBCP. Furthermore, Calgon Carbon cannot accept spent carbons that have certain RCRA test characteristics...ignitable below 150 F; pH less than 2.0 or greater than 12.5; or carbon that is reactive.

This thorough reactivation acceptance procedure, consisting of a series of analytical and business management steps, is undertaken for both the protection of Calgon Carbon and its customers. The procedure has undoubtedly contributed to the Company's successful operation of reactivation facilities since the early 1970's.

Step 2 - Proper System Design with Effective Carbon Transfer Design Features

A second key step in Calgon Carbon's reactivation process is proper adsorber and transport vessel design to insure a totally closed loop process. In Calgon Carbon's approach, it is first determined if off-site carbon reactivation is the most economical or the best option for the customer. When it is, then it is important that all spent carbon can be removed efficiently from the user site without worker exposure, safely transported in DOT approved equipment back to our reactivation facilities, efficiently unloaded at the reactivation site without worker exposure to the spent carbon and then properly stored/reactivated (as will be discussed below). This closed loop process begins with proper adsorption system design.

The adsorption system design will affect the loading of the carbon, the ability to remove all the carbon, carbon handling costs (time management), and the possibilities of worker or environmental exposure.

Calgon Carbon's pre-engineered systems are designed to (1) optimize on-site loading to help reduce reactivation costs, (2) remove all the spent carbon, (3) remove the carbon quickly thus minimizing handling costs, and (4) avoid all worker/environmental exposure. Suffice it to say, the choices for transporting spent carbon include (1) return of the vessel itself, (2) bulk back bins, or (3) specially designed, owned, and operated trucks. Since most carbon transport is in the trucks, this option is further discussed below.

Step 3 - Proper Spent Carbon Removal and Transport

Calgon Carbon operates a fleet of trucks which are designed

to be used with our Model 7.5, Model 10, Model 12 and Dual Adsorber Modules to completely remove and transport 10,000 - 20,000 lb. loads of carbon per carbon exchange. The operation of these trucks is quite simple. Transfers from them are made by creating a defense phase carbon slurry which is then transferred by air pressure. When a truck delivers new carbon to a site, the carbon can be transferred to the adsorber by pressurizing the truck hopper.

likewise, by pressurizing the spent carbon adsorber with air, spent carbon is transferred back to the truck for return to the reactivation facility. Depending on carbon requirements, transfer tanks may be located on-site to assist in the carbon transfers, or two trucks will be employed if that's the most economical alternative.

Some of the important steps Calgon Carbon takes relative to spent carbon removal and transport are:

Calgon Carbon provides customers supply assurance through its carbon manufacturing capabilities and operation of a private fleet of trucks, used exclusively for our carbons.

Every driver is specially trained in carbon transport/changeout procedures and must pass an annual recertification test.

Calgon's trailers are all fully licensed and insured up to \$6MM in case of an accident

All worker/environmental exposure is eliminated as the entire process is a totally closed loop process.

Step 4 - Proper Spent Carbon Storage and Reactivation

It is important to note that spent carbons returned to Calgon Carbon's reactivation facilities have been used in a variety of applications, most of which are not hazardous. The carbons may have been used to treat process water, for tertiary or secondary waste water treatment in industrial/municipal plants, for groundwater treatment, or for applications where dilute concentrations of dissolved organic contaminants have been removed. Typically, the spent carbon loads returned are about 50% activated carbon, 40% entrained moisture and 10-15% organic adsorbates. The prior reactivation test has provided critical information on how well this carbon will reactivate at various conditions. This information is all relevant to the reactivation process, as discussed below.

When the trailer full of spent carbon arrives at Calgon Carbon's reactivation plant, it is pneumatically transferred to specially designed and lined storage tanks. The carbon is stored therein under water at all times to protect against any release

to the environment. The storage tanks are located within a diked containment area and equipped with an overfill control system. They regularly undergo internal inspection and other preventative maintenance measures.

The specific spent carbon will be pumped as a slurry to a furnace feed tank and reactivated in Calgon Carbon's multiple hearth furnaces, which are classified as Resource Recovery unit operations under RCRA. The reactivation process drives off the adsorbates and oxidizes them to CO, water, acid gases, etc. Reactivation occurs at high temperatures in an inert atmosphere so that the adsorbates are destroyed, but most of the carbon is recovered for reuse. Furnace off gases are diverted to an afterburner where any residual hydrocarbon decomposition products are oxidized. The off gases are then sent to a scrubber where acid gases are neutralized. The gas then enters a baghouse filter system where neutral salts and particulates are removed. Solid wastes generated are stored on-site (in a hazardous waste designated area) until they can be transported off-site for proper disposal.

When the reactivated carbon exits the furnace, it is evaluated to insure that all adsorbed organic compounds have been driven off and destroyed.

The reactivated carbon is pumped to and stored in FRP tanks similar to the spent carbon storage tanks. They also are located in the containment area which includes a 10,000 gallon containment sump. A water treatment storage system is located next to the carbon storage tank and is used to store spent carbon slurry water and any other aqueous wastes generated, for subsequent treatment.

The reactivation sites at Neville Island, PA, and Catlettsburg, KY, are insured in the amount of \$6 million each to protect against sudden and accidental pollution. They have been successfully operating since the early 1970's and have reactivated more than 400MM lbs. of carbon safely and effectively. The plants are monitored around the clock to insure consistent attainment of all regulatory requirements.

Step 5 - On-Going Technical Services

Calgon Carbon provides reactivation customers an on-going commitment. That commitment includes providing many types of technical services. Should the waste change, as often is the case in groundwater applications, Calgon Carbon can provide a re-assessment of the process/system requirements using computer models or proprietary testing techniques. We re-evaluate our ability to provide safe carbon handling/transport and reactivation services, at least annually, as further detailed in our Waste Analysis Plan.

The Calgon Carbon reactivation facilities and program is a "state-of-art" effort that we believe no one else is currently prepared to offer. Our intent is very simple -- to help solve customer problems efficiently, economically and permanently. Calgon Carbon takes pride in helping customers rid the environment of organic contaminants, once and for always.

Use of Carbon Adsorption Processes in Groundwater Treatment

Mark H. Stenzel and William J. Merz

Calgon Carbon Corporation, P.O. Box 717, Pittsburgh, PA 15230

One of the leading treatment technologies for reduction of organic contaminants in groundwater has become the adsorption process utilizing granular activated carbon (GAC).

This paper presents a methodology for selecting the proper adsorption system design. The use of the isotherm test for evaluation of carbon adsorption is discussed, with new data on adsorption of VOCs presented. The use of the dynamic column study for system design and its relationship to the isotherm test is reviewed using actual case studies. Design and economics for full-scale GAC systems are discussed. The use of adsorption to remove organic contaminants from vapor sources resulting from groundwater treatment is also reviewed.

INTRODUCTION

The chemical process industry (CPI) may need to pump and treat groundwater for two different reasons: either to treat groundwater so it can be used as a resource, or to treat groundwater as part of a remedial activity. The treatment of groundwater so it can be used is becoming more common, as the CPI often faces the same problems as many municipal drinking water utilities in that even deep and heretofore clean aquifers have become contaminated with trace amounts of organic compounds. Removal of these compounds is often necessary before this water can be used. In the removal and treatment of groundwater as part of a remedial activity, the situation may reflect similarities to wastewater treatment, in that a CPI site cannot allow waste chemicals to migrate off-site, as would occur if contaminated groundwaters were allowed to flow untreated beyond the site boundaries.

In both categories, the organic contaminants of concern are, for the most part, chlorinated aliphatic and aromatic solvents, commonly referred to as Volatile Organic Contaminants (VOCs). These VOCs have become of primary concern as they have little affinity for soil, and thus rapidly pass through the soil and enter the aquifer. Once in the aquifer, the VOCs can migrate quickly in the groundwater and since they are often resistant to natural degradation, they can persist for long periods of time [1].

Adsorption with granular activated carbon (GAC) is a treatment technology that is now widely accepted for removal of these VOCs from groundwater. The acceptance of GAC adsorption is, in part, based on its long history of effectively removing organic contaminants from water

and wastewater. The CPI has used the adsorption process to purify water and a wide variety of products, and has used it as a physical treatment process in wastewater treatment.

In evaluating the use of GAC for the treatment of groundwaters, either for use or as part of a remedial activity, the investigator needs to properly define the problem and determine the applicability of alternative treatment technologies, including GAC. If GAC is to be evaluated, methods are available to accurately predict the capital and operating cost of applying adsorption treatment. These costs can then be compared to other applicable technologies, so that the most cost-effective solution can be selected.

TREATING GROUNDWATER FOR USE

In treating groundwater for use, the CPI is faced with many of the same problems as the drinking water industry, where small amounts of VOCs have been detected in potable water aquifers. The EPA, under the 1986 Amendments to the Safe Drinking Water Act (SDWA), is to generate Maximum Contaminant Levels (MCLs) for 83 specific contaminants by 1989. Many of these specific contaminants are VOCs. Limits have already been issued for eight such compounds, Table 1 shows four of these. These compounds are specifically regulated for drinking water. Many of the listed VOCs, which are now being detected in nearly 20% of potable groundwater supplies [2], may be detrimental to processes and products produced by the CPI.

TABLE 1. MAXIMUM CONTAMINANT LEVELS FOR FOUR CONTAMINANTS

Compound	MCL (mg/l)
Trichloroethylene	0.005
Carbon Tetrachloride	0.005
1,2 Dichloroethane	0.005
Benzene	0.005

The success of GAC in removing these types of organic contaminants has resulted in the SDWA Amendments stating that other treatment techniques must be at least as effective as GAC in order to be considered as a "Best Available Technology" [3]. Thus, GAC has been established as the benchmark technology, and its use should be considered in any evaluation of technologies for treatment of groundwater.

Evaluation Techniques—Adsorption Isotherms

A basic evaluation technique for activated carbon is the liquid-phase adsorption isotherm. The adsorption isotherm is a batch test designed to determine the equilibrium relationship between the organic compound(s) in the water, measured as concentration, and the organic compound(s) adsorbed on the activated carbon, expressed as weight of contaminant per unit weight of activated carbon (carbon capacity).

Isotherms have long been used as a preliminary evaluation tool for the use of GAC in wastewater treatment. When considering the adsorption of very low levels of VOCs, however, test conditions need to be carefully controlled to prevent the volatilization of the solvents while equilibrium is being obtained. Over the past four years, Calgon Carbon Corporation has generated a family of single component VOC isotherms for use by the water treat-

ment industry. Isotherm conditions were carefully selected so that reliable data points were obtained to better fix the isotherm plot. These conditions included the use of samples with no head space, long contact periods (20 hours) to assure equilibrium, relatively large quantities of powdered GAC to minimize weighing errors, and the use of relatively large concentrations of VOCs to minimize analytical errors [4], [5].

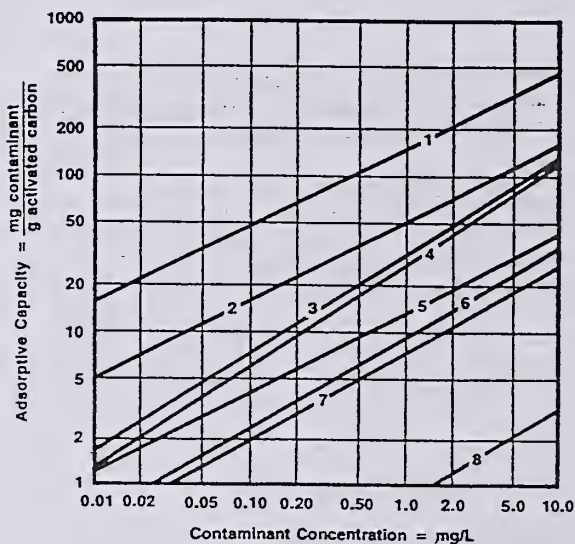
Figure 1 shows the results of single component isotherms for selected chlorinated aliphatic solvents. Figure 2 shows results of single component isotherms for some aromatic solvents. It is important to note that the testing protocol must be consistent when comparing the relative adsorbability of one compound to another, or when considering the effect of concentration changes.

Isotherms are useful in identifying whether activated carbon will be an effective treatment. In fact, when considering GAC treatment, isotherms such as these can be a valuable screening tool. Isotherms will also be useful in determining the effect of decreasing contaminant concentration, especially when used in conjunction with dynamic testing or actual operating results.

Prediction of Design and Usage Rates

The normal sequence of evaluation would be to follow the batch isotherm test with a dynamic column study to fix system size (contact time) and actual carbon usage rates so that a complete economic analysis can be done. If the contamination problem is simple, however, the isotherm test can be utilized to predict these parameters.

Often water drawn from deep aquifers is contaminated with only one or two organic compounds that require removal, and little background contamination from other organic material is present. In this situation, the investigator can have some confidence in determining the system design, using historical column test data to corroborate the estimates.



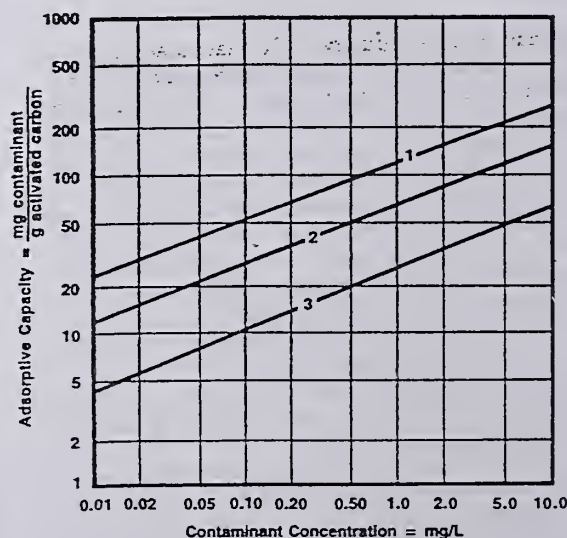
ISOTHERM CONDITIONS:

Sample Volume = 137 ml
Temperature = Ambient
Agitation Time = 20 hours
Carbon = Filtrasorb 300

ISOTHERM IDENTIFICATION

1. Tetrachloroethylene
2. Trichloroethylene
3. Carbon Tetrachloride
4. 1,1,1-Trichloroethane
5. 1,1-Dichloroethylene
6. Chloroform
7. 1,2-Dichloroethane
8. Methylene Chloride

Figure 1. Single contaminant adsorption isotherms for chlorinated aliphatic solvents.



ISOTHERM CONDITIONS:

Sample Volume = 137 ml
Temperature = Ambient
Agitation Time = 20 hours
Carbon = Filtrasorb 300

ISOTHERM IDENTIFICATION:

1. m-Xylene
2. Toluene
3. Benzene

Figure 2. Single contaminant adsorption isotherms for aromatic solvents.

TABLE 2. ACCELERATED COLUMN TEST STUDIES LOW LEVEL/SINGLE CONTAMINANT CASES

Site:	Municipal groundwater	Synthetic groundwater	Synthetic groundwater	Municipal groundwater
Contaminant	Trichloroethylene	Trichloroethylene	Trichloroethane	Chloroform
Concentration, ppb	30	202	205	126
Effluent objective, ppb	1	1	1	1
Contact time, minutes	10	8.5	8.5	12
GAC usage rate, pounds/1000 gals.	0.07	0.12	0.36	0.9
Realized capacity mg/gm	3.6	14.1	4.8	1.2
Isotherm (equilibrium) capacity, mg/gm	8.0	27.0	8.8	2.6
Percent of equilibrium capacity realized	45%	52%	54.5%	46%

8.33 lb/1000 gallons = kg/m³.

Calgon Carbon Corporation has conducted many column studies on contaminated potable groundwaters using a rapid small-scale column test [6]. These tests, using a single short column, small size granules, and mathematical modeling, have proven to be effective in predicting dynamic performance that has been shown to be similar to scaled-column studies [7] and actual system operation. The advantage of the rapid test is that the results can be obtained in a much shorter time frame, requiring less sample and less cost for analysis and manpower.

These "Accelerated Column Tests" (ACTs) have been used to model the system performance by evaluating contact times and determining carbon usage rates. Table 2 shows the results of ACTs run on actual and synthetic groundwater samples [5]. The actual groundwaters tested had low background organic contamination (<0.5 ppm TOC). These tests show that operating systems with short contact times can obtain 45–55% of the theoretical, or equilibrium, capacity of GAC at the time of "breakthrough," which is when the VOC first appears in the effluent. These tests also indicate that these contaminants adsorb in a relatively short adsorption zone, which means that little available adsorptive capacity will remain upon breakthrough.

Based upon the historical ACT data, a preliminary system design for removal of one or two VOCs from a "clean" groundwater would include a single-stage adsorber with 12–15 minutes contact time, calculated on an empty-bed basis. A single stage adsorption system will minimize equipment costs, and based on a low GAC usage, will optimize overall treatment costs. The operating GAC usage rate can be estimated at 45–55% of the capacity shown by the isotherm.

A column test such as the ACT would be recommended if there were more contaminants present or if there was a substantial amount of background organic matter. In some areas of the country, even clean groundwaters may contain up to 8–12 mg/l of background organic matter; reported as TOC, which may adversely affect adsorption of the specific contaminants of interest. An ACT is also recommended if a more accurate prediction of carbon usage, using the actual water to be treated, is deemed necessary.

Adsorption System Design and Economics

The downflow, fixed-bed adsorber is the simplest and most widely utilized design for groundwater treatment applications. The water enters the top of the adsorber, is

equally distributed across the GAC by the packed, flooded-bed design, and is collected by slotted screen collectors across the bed cross-section at the bottom of the vessel. The fixed-bed design can be either of the gravity or pressure type. The pressure type is normally recommended as it will occupy less space because it uses higher surface loading rates (up to 10 gpm/ft², 0.0068 m/s), and generally, repumping of the treated water will not be required. A fixed-bed pressure adsorber is usually an ASME coded carbon steel pressure vessel with a corrosion resistant lining. A single-stage adsorber is often provided with in-bed sampling ports, if the breakthrough of contaminants needs to be anticipated.

Typically, 10 ft (3.048 m) diameter adsorption vessels containing 20,000 lbs. (9080 kg) of GAC are used for groundwater treatment service. This size adsorber and GAC quantity has become an accepted standard size, as the spent GAC from a single unit can be transported from the site in a single trailer. The GAC quantity limitation is due to transportation considerations, as the entire quantity of GAC, retained pore water, and adsorbate will weigh approximately 40,000 lbs (18,160 kg). Each of these adsorbers can treat up to 350 gpm (0.022 m³/s) at a contact time of 15 minutes, and an overall system pressure drop in the range of 15 psig (0.1 Mpa).

The following example shows how the preliminary economics can be obtained for a groundwater treatment scenario. The assumptions for the groundwater source are:

Flow:	300 gpm (0.019 m ³ /s)
Contaminant:	Trichloroethylene
Concentration:	180 µg/l (ppb)
Desired Effluent Conc:	<5 µg/l (ppb)
Background Organic Content:	Negligible (<0.5 ppm)

Based upon the evaluation procedure and information provided, the following preliminary process design can be made:

Adsorbers:	One 10 ft. (3.048 m) dia. adsorber
GAC:	20,000 lbs. (9,080 kg)
Contact Time:	17 minutes (empty bed basis)
Equilibrium Capacity:	25 mg TCE/gm GAC (Figure 1)
% Equil. Capacity Expected to be Realized	50% at breakthrough
Estimated GAC Capacity:	12.5 mg TCE/gm GAC
Estimated GAC Usage:	0.12 lb. GAC/1,000 gal. (0.0145 kg/m ³)
Estimated Annual GAC Usage:	20,000 lbs. (9,080 kg)

A single adsorber, complete with process, utility, and

TABLE 3. ADSORPTION SYSTEM ANNUAL COSTS LOW LEVEL/SINGLE CONTAMINANT

Amortization of capital (8.75% interest/20 years)	\$13,400
Maintenance (5% of installed capital)	6,250
Energy costs (3.5 BHP for additional 15 psig; 8¢/KWH)	2,400
GAC usage ¹ (20,000 lb. Calgon F-300; \$0.90/lb.)	18,000
GAC freight (one bulk delivery)	2,750
Total annual cost	\$42,800
Unit cost	\$0.27/1000 gal.

¹ Assumes supplier of GAC can remove spent carbon and arrange for disposition or reactivation in an environmentally safe manner.

carbon transfer piping, and provided with 20,000 lbs (9080 kg) of GAC can be installed on an existing foundation for approximately \$85,000. A foundation, well pump upgrade (if necessary), tie-ins to the existing system, and project management might result in a total capital expenditure of approximately \$125,000 for a complete 300 gpm (0.019 m³/s) system.

The annualized operating cost is shown in Table 3, which results in a complete treatment cost of approximately 27 cents for each 1,000 gallons treated. This amount assumes that the supplier of the fresh GAC will be capable of removing and safely handling the spent GAC, or possibly reactivating it for reuse. This cost is in general agreement with EPA estimates of 34 cents per 1,000 gallons (3.78 m³), based upon systems below 1 MGD (3785 m³/day) providing 99% removal of TCE at a 500 ppb or less initial concentration [8]. Also, in a survey of similar applications with low contaminant levels and single-stage adsorption, Calgon Carbon estimated treatment costs in the range of 22 to 55 cents per 1,000 gallons (3.78 m³) [9].

TREATING GROUNDWATER FOR REMEDIATION

In dealing with remediation activities, the most important factor is that the groundwater is withdrawn at a rate at least sufficient to prevent the migration of the contamination, or preferably, to capture the contamination and eventually remove the contaminants from the site. After establishing the water pumping rate, there are numerous methods of treatment available, depending on site-specific situations. Of primary concern is the degree of treatment required. A checklist for degree of treatment would vary, depending on whether the water will ultimately be sent to a wastewater treatment facility, either in an existing plant or off-site POTW, whether it will be discharged under existing permits, or whether it will be recharged into the aquifer. If discharged to an existing treatment facility, for example, it is likely that point source treatment will be needed to reduce volatile and biologically resistant or toxic contaminants.

Once the flow, contaminants, and degree of treatment are fully defined, an evaluation of potential treatment processes can be made. For the type of organic compounds prevalent in contaminated groundwaters, especially chlorinated aliphatic and aromatic solvents, adsorption with GAC has proved to be a highly effective treatment.

The groundwaters withdrawn in remediation projects often contain a complex mix of contaminants. If drawn from a shallow aquifer, the groundwater may also contain other organic compounds, such as natural occurring

humic substances. The type of other organic compounds present may influence carbon usage, even though their removal is probably not required. Poorly adsorbed compounds, for instance, will have little effect on usage rates, whereas more strongly adsorbed compounds will competitively adsorb with the contaminants of concern and adversely affect usage rates. For such cases, the isotherm evaluation can only be used as a preliminary screening tool. Published single-component isotherms can establish whether the compounds of interest are amenable to adsorption, and which compounds will likely control the cost-effectiveness of carbon treatment. Isotherms conducted on the specific groundwaters, and perhaps evaluated on a TOC (Total Organic Carbon) basis will show the presence of background organic compounds and will indicate what portion of these can be deemed non-adsorbable. If carbon treatment is viable, however, one needs to use more advanced evaluation to completely fix the performance and economic parameters.

Evaluation Techniques—Column Studies

If a review of the isotherm data establishes that GAC is a viable treatment technique, a scaled-column study can be conducted to observe the breakthrough characteristics. Based on proper selection of contact times, a carbon usage rate can be established for economic analysis. The isotherm review will also establish the least adsorbable contaminant of interest, so that a column study can be monitored for breakthrough of only that contaminant to simplify the analysis and reduce analytical costs. Although the scaled-column test is the best technique to define GAC system parameters, there can still be physical problems with the handling of water containing volatile contaminants, and the time and expense involved with such a study can be significant.

The rapid, small-scale column test, such as the ACT, is often a good means of obtaining dynamic data within a short period of time. Knowledge of the flow rate and influent characteristics is usually sufficient to select a contact time. This information, coupled with the understanding of what will be an economical adsorption system size for the actual site, would help select the contact time ultimately modeled. With the use of an actual field sample, the ACT will take into account actual operating situations; including the mass transfer zones as determined by the kinetics of adsorption and competitive effects of multiple components. The ACT will provide information on usage rates at breakthrough and saturation for the contaminants under consideration, which will be useful in determining system configuration and the degree of treatment for the economic analysis.

Table 4 shows the results of a variety of ACT studies conducted by Calgon Carbon on actual groundwater samples. These samples show a cross section of examples that might be expected in remedial activities, such as cleaning groundwaters from spills, leaking underground tanks or pipelines, leachates from dump sites, or from normal industrial activity. Before running these studies, it was determined that adsorption was an applicable treatment, but that more information was needed to confirm the system design and carbon usage rates.

Cases 1 and 2 show situations that are relatively simple and exhibit low GAC usage rates; indicating that a single-stage adsorption system would still be the optimum system. Case 1 also indicates that, due to the relatively higher concentration of trichloroethylene, a higher driving force toward equilibrium results in 60% of the equilibrium capacity of the isotherm being realized.

Case 3 covers a situation in which a poorly adsorbed contaminant is present in the mixture. Combined with

TABLE 4. ACCELERATED COLUMN TEST STUDIES GROUNDWATER FROM REMEDIATION SITES (ACTUAL SITE SAMPLES)

Case	Simulated conditions		Adsorbates		At breakthrough		At saturation	
	Loading gpm/sf	Contact time min.	Contaminant (order of breakthrough)	Concentration mg/l	GAC load mg/gm	lbs/1000 gallons	Effluent conc. mg/l	lbs/1000 gallons
1	3.8	18	Trichloroethylene	3.3	61	0.45	0.001	—
2	2.0	35	Benzene	0.024	0.5	0.4	0.002	—
			Toluene	0.116	2.4	0.4	0.002	—
			Xylene	0.530	13	0.4	0.001	—
3	3.5	20	Methylene chloride	0.007	0.014	5.8	0.001	5.2
			Chloroform	0.268	3.8	0.8	0.004	0.7
			Cis-1,2-Dichloro- ethylene	0.118	2.6	0.5	0.001	0.46
			Carbon tetrachloride	39.8	—	—	—	—
4	3.8	20	1,2-Dichloroethane	0.095	0.13	5.9	0.003	4.0
			Chloroform	0.223	0.37	5	0.010	4.0
			Carbon tetrachloride	3.08	6.4	4	0.010	—
5	1.3	100	Benzene	0.034	3.1	3.0	0.003	2.0
			Toluene	4.6	79.0	3.0	0.125	2.1
			Xylene	4.1	—	—	—	—
6	1.3	44	TOC	150	—	—	55	—
			Benzene	10.2	7.7	11	0.002	—
			Toluene	8.2	9.7	7	0.002	—
7	2.6	22	TOC	15	—	—	15	—
			Phenol	44	147	2.5	0.04	1.1
			Benzene	0.44	4.6	0.8	0.33	0.74

1470 gpm/sf = m/s

other VOCs, the presence of methylene chloride results in a relatively high carbon usage rate, if the methylene chloride is to be removed to non-detectable levels. The designer has several options available in designing an adsorption system for this situation. One option is to add a second stage to the process to allow the first stage to reach saturation, thereby reducing the carbon usage rate by approximately 10%. A second option, depending upon the disposition of the water and the applicable treatment limits, is to allow the methylene chloride to break through the carbon system and remain in the effluent or allow downstream mixing to reduce the concentration. Third, the use of a combination of technologies can be considered for a case like this. Finally, the designer may expect the concentration of the methylene chloride to diminish over time and disregard its effect on the usage rate. For the last two cases, the economic analysis would be based on removal of the remaining VOCs, which, in this example, would be determined by chloroform removal.

Cases 4 and 5 both exhibit the benefit in adding a second stage to an adsorption system, especially when working with a mixture of contaminants in the mg/l range. In these cases, a 30–32% decrease in carbon usage rate was realized by allowing the carbon to obtain full utilization for the contaminant. In Case 5, involving aromatic solvents, although benzene is more poorly adsorbed than toluene, both contaminants breakthrough and reach saturation at about the same time due to the much greater concentration of the toluene.

In some situations, one contaminant may be present to a much greater extent than the other compounds in a mixture. In certain examples, such as Cases 3 and 4, these contaminants will adsorb preferentially and other contaminants will breakthrough first. In other examples, such as Case 5, the predominant contaminant may breakthrough first. The designer may have to monitor for both the predominant contaminant and the less adsorbable contaminants in order to determine the carbon usage rate.

Cases 6 and 7 illustrate the effect of the presence of other organic compounds that need not be controlled by the treatment process. As discussed earlier, the adsorbability of these organic compounds may influence the ad-

sorption of the contaminants of interest. The ACT test should determine the overall effect of such compounds on the usage rate for removal of specific contaminants under consideration. In Case 6, the presence of 150 mg/l TOC increases the carbon use rate for benzene and toluene above that which might have been expected after observing Case 5. In Case 7, a non-volatile contaminant, phenol, is adsorbed to a greater degree than benzene, but it will breakthrough first, due to its higher concentration and solubility. Due to the adsorption of phenol, the capacity of GAC for benzene is adversely affected. For this case, addition of the second stage will improve usage rates for the phenol and benzene.

These column studies illustrate some of the design decisions that need to be made when conducting an analysis of GAC treatment. Consideration of a second stage may improve carbon usage and optimize the treatment cost. Knowledge of effluent requirements will determine the proper control point for the adsorption process, and an understanding of impacts of change in influent levels may influence the selection of the treatment process.

Adsorption System Design and Economics

As a remedial treatment would likely encounter a mix of contaminants or contaminant concentration in the mg/l range, a staged adsorption system design would generally be recommended to minimize carbon usage and optimize treatment costs. Multiple pressure vessel systems, normally two units, will achieve the staged process design. The second unit will continue to adsorb contaminants, while the first stage is allowed to become more or less fully saturated for the contaminants. When the first stage is refilled with fresh GAC, it is then returned to service as the second stage unit. To allow for return of the spent GAC in the same trailer that delivered the fresh GAC, a transfer tank is often used to temporarily hold the spent GAC while the fresh GAC is unloaded into the adsorber. The GAC usage rate will normally determine whether the inclusion of a transfer tank is economically attractive.

Activated carbon treatment of groundwaters with contaminants in the mg/l range will likely result in higher

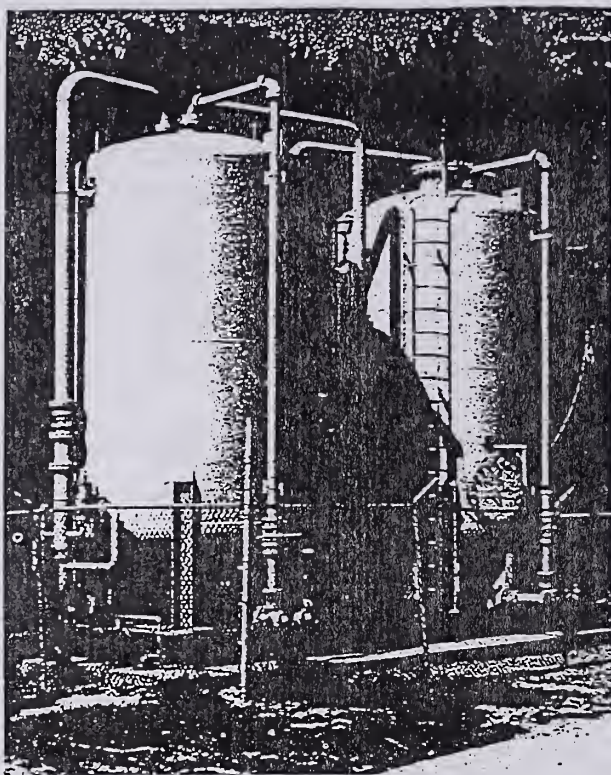


Figure 3. Two-stage adsorption system. This photo illustrates an installed two-stage adsorption system. Each adsorber is a 10 ft. (3.048 m) diameter vessel containing 20,000 lbs. (9080 kg) of granular activated carbon. The system is skid mounted for ease of installation and pipe support. This site treats 350 gpm (0.022 m³/s) for groundwater treatment.

carbon usage rates and greater contaminant concentrations on the spent carbon. The advantage of carbon adsorption is that these contaminants have been concentrated and can be retained in the carbon granule for transport. If the spent carbon is sent to a thermal reactivation process, the contaminants will be thermally destroyed in the process and the carbon can be reused.

Each individual adsorber in the staged system would be similar to the single-stage adsorber described previously, with a piping network utilized to effect the staging procedure. Figure 3 shows a typical two-stage adsorption system using two 10 ft. (3.048 m) diameter adsorbers, each of which contains 20,000 lbs (9080 kg) of granular activated carbon.

The following example illustrates an economic analysis, using Case 5 as a basis. Assuming that benzene, toluene, and xylene are to be reduced to non-detectable

levels, a two-stage system is selected to assure both the achievement of this effluent level and to minimize GAC usage. The following process design was selected:

Flow:	200 gpm (0.0126 m ³ /s) (24 hrs./day, 345 days/yr.)
System:	two-stage plus transfer tank
Quantity GAC:	20,000 lbs. (9,080 kg) per stage
Contact Time:	26 minutes/stage
GAC Usage:	2 lbs./1,000 gallons treated (0.24 kg/m ³)

It is assumed for this example that the carbon usage rate from the column study is obtainable at shorter contact times. The capital cost for the two-stage system, with transfer tank, is predicted to be \$350,000, utilizing the same assumptions as for the single-stage system.

The breakdown of the annualized operating cost is shown in Table 5 which results in a treatment cost of approximately \$2.47 per 1,000 gallons (3.785 m³) treated. The largest portion of this operating cost is due to the ongoing cost of GAC. Any reduction in influent concentration will be directly reflected in savings in carbon cost. In the survey cited earlier [9], Calgon Carbon estimated costs in the range of 48 cents to \$2.52 per 1,000 gallons (3.785 m³) treated for similar situations, using two-stage adsorption systems and recycling the activated carbon via thermal reactivation. The choice on how to handle the spent carbon is an important decision in any application of carbon adsorption, but particularly so in remedial treatment, where carbon usage is higher.

Reactivation offers a number of advantages over disposal, including lower cost in most cases, plus the assurance that reactivation, if properly done, will destroy the adsorbed contaminants in the process and remove them from the environment. While reactivation can theoretically be performed on-site, most of these types of projects will have too low a carbon usage to justify on-site reactivation, and reactivation will be performed off-site by a company offering reactivation services. Spent carbons from remediation projects, in particular, will often be considered a hazardous waste under the RCRA regulations. If the spent carbon is manifested as a hazardous waste, it is important that the company accepting the spent carbon have all requisite RCRA and other permits, and that the facility affords protection against occurrence of environmental incidents. It is also in the generators interest that the provider of reactivation services have the necessary insurance coverages and resources to properly indemnify the generator of the spent carbon against a potential liability for improper carbon handling.

Pretreatment for Carbon Adsorption Systems

At times, groundwaters from remedial activities may be complex in nature and multiple treatment steps may be required, of which carbon adsorption may be an integral part to remove specific organic contaminants to non-detectable levels. If the pre-treatment system to the GAC adsorption system includes precipitation of settling steps for metals or suspended solids removal, it is recommended that filtration be included in the design. While granular carbon itself is an excellent filtration medium, it may develop high-pressure drop faster than a unit process designed for more in-depth filtration. Also, pressure filters often utilize smaller diameter units operating at higher surface loading rates and, thus, required less backwash water. If a carbon unit is operating alone as a treatment step, however, it is recommended to include a backwash or backflush capability so that the unit can be kept in operation for the full life of the GAC.

TABLE 5. ADSORPTION SYSTEM ANNUAL COSTS REMEDIAL SITE—CASE 5

Amortization of capital (8.75% interest/20 years)	\$ 37,600
Maintenance (5% of installed capital)	17,500
Energy costs (3.5 BHP for additional 15 psig; 8¢/KWH)	2,400
GAC usage ¹ (20,000 lb. Calgon F-300; @ \$0.80/lb.)	160,000
GAC freight (10 bulk trailer deliveries)	27,500
Total annual cost	\$245,000
Unit cost	\$2.47/1000 gal.

¹ Assumes supplier of GAC can remove spent carbon and arrange for disposition or reactivation in an environmentally safe manner.

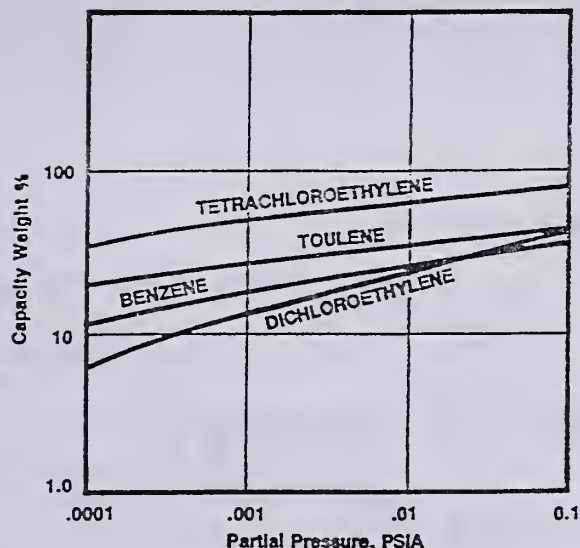


Figure 4. Vapor phase isotherms.

Another step that may precede adsorption is air stripping for removal of the most volatile contaminants. In many cases, the air stripping process can remove the bulk of the VOCs ahead of the adsorption unit, greatly reducing the carbon usage rate needed to remove the overall VOCs to non-detectable levels. This approach could, for example, be considered for the methylene chloride case (Case 3) previously discussed. If an air stripper system is considered, all of the operating expenses for an air stripper need to be taken into account. These expenses include downtime for cleaning and disposal of cleaning chemicals used for controlling scaling and fouling, and repumping the effluent. Possible influent variation, change in contaminant mix, effect of non-volatile contaminants, and potential requirements for off-gas treatment may result in the air stripper not reaching treatment objectives, and added expense for design changes or additional treatment.

For relatively clean groundwaters, it may be more economical to remove the VOCs by air stripping and use adsorption with GAC to remove them from the air stream, as vapor phase GAC has more capacity for organic contaminants adsorbed from air than liquid phase GAC has for the same contaminants in water.

ADSORPTION OF CONTAMINANTS FROM AIR SOURCES

Two aeration techniques that are finding acceptance in removing VOCs at remedial sites are air stripping for removing VOCs from groundwater, and *in-situ* soil air stripping that removes VOCs from the unsaturated zone above the water table. In both cases, VOCs are transferred to a vapor stream that may require treatment to remove the contaminants before they are released to the environment. Carbon adsorption is widely used in this application, as it has for many years been a well-established technology for removing organic compounds from vapor sources, such as solvent recovery operations in industry and odor control in wastewater treatment.

Evaluation Techniques—Adsorption Isotherms

As with the liquid phase evaluation, the vapor-phase adsorption isotherm is the basic evaluation technique for

removal of organic contaminants from air. The compilation of single component isotherms in Figure 4 show the greater capacity for the contaminants in the vapor phase. This phenomena is partly explained by the structure of the vapor phase carbons compared to the liquid phase carbons, and partly due to the behavior of the solvents in their vapor state. In general, preliminary vapor phase carbon usage can be predicted by adding the carbon usage generated by each individual contaminant, as competitive adsorption effects are less of a concern in the vapor phase than in the liquid phase. The isotherm prediction assumes relatively low moisture in the vapor, as high moisture (greater than 50% RH) can cause the GAC pores to fill with water and adversely affect the predicted vapor phase capacity.

Design of Vapor Phase Adsorption Systems

The choice of vapor-phase adsorption systems is usually between one of two basic processes: regenerable and non-regenerable adsorption systems. The choice between the two systems is based on economics, with particular consideration given to the expected life of the remedial project. In *in-situ* soil-stripping processes, for example, the initial organic loading may be high, but then it often falls off rapidly in an asymptotic manner [10], so that the design of choice is nearly always a non-regenerable type when the project life is taken into consideration. For air stripper systems, however, a regenerable system may be more economical than one in which the carbon is replaced and disposed of on a frequent basis.

In a non-regenerable system, the contaminated air is passed through the adsorption system and discharged. If the contaminated air is from an air stripper, the air may be heated by approximately 25–30°F (14–17°C) to reduce the humidity to less than 50%, thus providing for greater adsorptive capacity by minimizing the tendency for water vapor to condense and fill the pores of the GAC. The capital cost for a non-regenerable systems is generally low, as adsorbers and duct are often constructed of FRP. The size of the vessel is determined by two factors. The vessel diameter is determined by the air flow rate, often in the range of 40–80 fpm (0.2–0.4 m/s) face velocity and the bed depth of GAC, normally 3 to 5 ft. (0.9–1.5 m) depth, depending upon the frequency of exchange required.

Vapor-phase adsorption occurs in a very short depth of the bed, so relatively short bed depths can be employed, as compared to the deeper bed depths normally used in liquid phase systems.

The equipment cost of a vapor phase adsorption system is approximately equal to the equipment cost of the air stripping equipment it is associated with. The cost of carbon on a per pound basis may be two to three times that of liquid phase GAC, as the price for vapor phase carbon is higher, and spent carbon handling costs may be higher due to the higher contaminant loadings obtained in the vapor phase.

In a regenerable vapor-phase adsorption system, the GAC can be regenerated in place. The regeneration of GAC in vapor-phase service requires less severe conditions than that required for regeneration of liquid phase carbons since there is a low level of moisture in the carbon particle. Also, the adsorbed organic compounds are volatile to begin with and are more easily desorbed from the carbon surface. Liquid-phase systems also will tend to adsorb many non-volatile compounds and other organic compounds that are not easily desorbed. The use of regenerable systems becomes economical when the carbon exhaustion rate is high, and the amount invested in regenerable systems is offset by the savings in the cost of purchasing replacement GAC.

The steam regenerable system, as is often used in solvent recovery operations, is the most common type of regenerable system. In this process, contaminated air is passed through one of two carbon adsorbers and then discharged. While one adsorber is on line, the second is regenerated by heating the GAC to about 220°F (105°C) with steam. The steam carrying the desorbed organic contaminants is then cooled in a condenser, and the condensate is collected for disposal.

The capacity of GAC for the contaminants in a steam regenerable system is often less than for fresh GAC. This working capacity of the GAC is determined by the type of contaminants being desorbed and the degree of removal required. In many cases, this working capacity may be less than 20% of the capacity of fresh GAC due to retention of adsorbed contaminants in the small carbon pores.

There are newer processes available that can be used when a more complete regeneration is desirable. A more complete removal of adsorbed contaminants can be effected using a hot inert gas, nominally at 350°F (175°C), for in-place regeneration. This hot gas regeneration recovers a greater portion of the working capacity than is obtained with steam regeneration. The organic contaminants desorbed and carried with the hot gas can be removed by cooling or can be oxidized by sending the gas directly to a thermal oxidizer. This type of regenerable system may be especially viable if disposal of condensate from a steam regenerable system becomes a major factor, or if the goal is to obtain complete destruction of contaminants at the site [11].

CONCLUSION

The need to remove organic contaminants from groundwater, either to insure safety of the groundwater resource or to remediate an underground wastewater problem, has become a widespread concern of the CPI. Adsorption with granular activated carbon is a widely accepted technology for removal of these contaminants, and normally should be an integral part of an investigation of treatment alternatives.

Both a historical data base for screening the applicability of GAC and evaluative techniques to determine the economics of treatment exist to establish the cost effectiveness of adsorption. The procedure presented here will hopefully be helpful as a point of reference to evaluate other treatment technologies and as a planning technique for the employment of activated carbon adsorption.

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There is an Answer to Groundwater Contamination

by Robert P. O'Brien and J.L. Fisher

During the last few years much valuable experience has been gained in treating water containing organic contaminants with granular activated carbon.

There is an Answer to Groundwater Contamination

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With increasing regularity, many areas of the U.S. are finding the groundwater from which they draw their potable supplies are contaminated with potentially hazardous organic compounds. Industry, government and the public now recognize that haphazard and improper waste disposal practices in the past, chemical spills, and leachates from lagoons and dumpsites are major causes of groundwater contamination.

What is not so well known is that there is a proven technology which is being used more and more to treat and purify contaminated groundwater.

That technology is adsorption with granular activated carbon (GAC), and a significant amount of operating experience has now been obtained. Results from 31 operating plants that employ granular carbon to remove toxic organic compounds from groundwater supplies are now available in detail. These plants have been treating contaminated flows ranging from 5 to 2,250 gpm, and the knowledge gained from running these facilities promises to be valuable in implementing future groundwater strategies and treatment.

The causes of the groundwater con

tamination at the 31 different sites for which Calgon Carbon Corporation provided carbon adsorption equipment and adsorption technology were classified three ways: leachate from lagoons and dumpsites; industrial accidents and spills; and spills resulting from railroad or truck accidents. Industrial accidents accounted for 22 out of the 31 sources (Table 1).

As these sources of contamination are different, so too are the reasons for groundwater treatment. The same table shows that in 15 of the 31 cases, carbon treatment was applied to prevent the spread of contamination throughout an aquifer. This was accomplished by drilling purge wells around the site of a spill or accident. These wells were pumped at a set rate

to create a cone of depression and prevent further migration or spread of the organic contaminants. Granular carbon systems were used to treat water from the purge wells prior to discharge to a receiving stream, re-injection to the well field, or reuse.

A further twelve carbon systems were used for the purification of potable water, and the remaining four were operated for the decontamination of plant process water. Since the wells already existed in these situations, granular carbon systems, designed for pressure operation, were easily added to well discharge lines.

Data available from these treatment systems clearly show the ability of GAC to remove a wide range of organ-

Table 1

Aquifer Contaminated By	Occurrences
Leachate from lagoons or dumpsites	4
Industrial accidents (chemical spills, tank leaks)	22
Chemical spills due to railroad or truck accidents	5
Total	31
Primary Reason for Treating Groundwater	Occurrences
Clean-up of aquifer (with purge wells) to prevent spread of contamination	15
Plant process water use	4
Potable use	12
Total	31

Table 2

Organic Compounds In Groundwater	Number of Occurrences	Influent* Concentration Range	Carbon Effluent* Concentration Achieved
Carbon tetrachloride	4	130 ug/l-10 mg/l	<1 ug/l
Chloroform	5	20 ug/l-3.4 mg/l	<1 ug/l
Dibromochloropropane	1	2-5 mg/l	<1 ug/l
DDD	1	1 ug/l	<.05 ug/l
DDE	1	1 ug/l	<0.05 ug/l
DDT	1	4 ug/l	<0.05 ug/l
CIS-1,2-dichloroethylene	8	5 ug/l-4 mg/l	<1 ug/l
Dichloropentadiene	1	450 ug/l	<10 ug/l
Diisopropyl ether	2	20-34 ug/l	<1 ug/l
Tertiary methyl-butylether	1	33 ug/l	<5.0 ug/l
Diisopropyl methyl phosphonate	1	1,250 ug/l	<50 ug/l
1,3-dichloropropene	1	10 ug/l	<1 ug/l
Dichloroethyl ether	1	1.1 mg/l	<1 ug/l
Dichloroisopropylether	1	0.8 mg/l	<1 ug/l
Benzene	2	0.4-11 mg/l	<1 ug/l
Acetone	1	10-100 ug/l	<10 ug/l
Ethyl acrylate	1	200 mg/l	<1 mg/l
Trichlorotrifluoroethane	1	6 mg/l	<10 ug/l
Methylene chloride	2	1-21 mg/l	<100 ug/l
Phenol	2	63 mg/l	<100 ug/l
Orthochlorophenol	1	100 mg/l	<1 mg/l
Tetrachloroethylene	10	5 ug/l-70 mg/l	<1 ug/l
Trichloroethylene	15	5 ug/l-16 mg/l	<1 ug/l
1, 1, 1-trichloroethane	6	60 ug/l-25 mg/l	<1 ug/l
Vinylidene chloride	2	5 ug/l-4 mg/l	<1 ug/l
Toluene	1	5-7 mg/l	<10 ug/l
Xylenes	3	0.2-10 mg/l	<10 ug/l

*Analyses conducted by Calgon Carbon Corporation conformed to published U.S.EPA official methods. Tests in the field were conducted using available analytical methods.

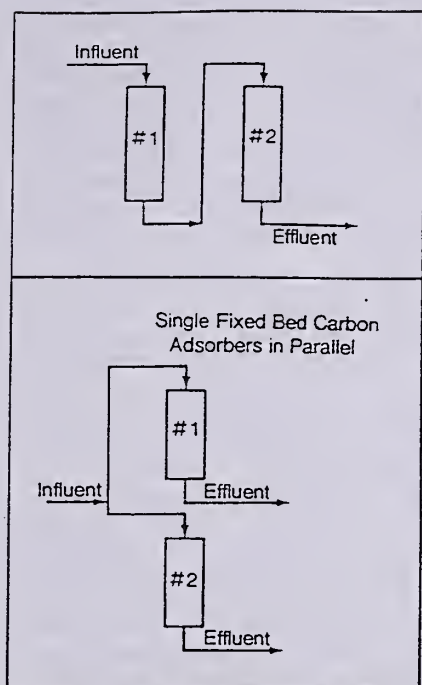


Figure 1. Carbon adsorbers in series operation (top); carbon adsorbers in parallel, single fixed bed operation (below).

ic compounds. Table 2 (page 30) lists the organic compounds found in the groundwater supplies along with their influent and effluent concentrations before and after treatment. Even though the type and concentration of the organics varied from location to location, the GAC process consistently reduced them to levels below detectable limits. Thus, all 31 operating systems demonstrated that a properly designed granular carbon system can produce very high-quality water from a contaminated groundwater supply.

Trichloroethylene and tetrachloroethylene were the most frequently detected compounds at the treatment sites. They are used extensively in industry as metal degreasers, drying agents and extraction solvents.

A few of the aquifers had extremely high levels of contamination, with an organic total above 100 mg/l (parts per million, ppm). However, most groundwater applications call for the removal of contaminants with concentrations in the low mg/l or lower still in the ug/l (parts per billion, ppb) range. The ability of GAC to effectively remove low as well as high concentrations of organics is an important consideration.

Having designed and operated over 250 fixed bed units, in both series and parallel configuration, and over 150 moving bed units, our experience with both types of adsorption systems has demonstrated that a downflow fixed bed is more cost-effective than a pulsed bed for groundwater treatment. This is especially true in those applications where the carbon usage rate is nominal and the adsorption wavefront

is short (e.g. 2 to 3 ft vs. 30 to 40 ft in some process applications). In fact, a properly designed fixed bed can operate with the same carbon usage rate as a pulsed bed, yet costs less to build.

Each adsorber at the treatment sites had a capacity of 20,000 lb, or a full truckload, of granular carbon. The size of the units allowed the carbon to be handled in bulk, which reduced freight. Each adsorber also contained a proven underdrain system comprising a pipe lateral network with nozzles.

Spent or exhausted carbon was always removed when organics were detected in the system effluent. Carbon removal was accomplished by using air pressure for automatic transfer out of an adsorber unit as a slurry. The slurry was piped to a waiting truck which returned the carbon to a reactivation center. The entire transfer procedure was accomplished in a closed system with no worker exposure to the carbon.

At 22 of the 31 sites, treatment of groundwater prior to carbon adsorption was not required. These contaminated groundwater supplies were stable and contained low concentrations of suspended solids which could be removed in the carbon bed without impeding adsorption or creating a high pressure drop. Thus pH adjustment, prefiltration or backwashing of the carbon adsorbers was not necessary. The hydraulic surface loading ranged from 0.25 to 9.6 gpm sq/ft.

Seven of the locations employed multi-media filtration ahead of carbon adsorption as a safety factor because the quality of the contaminated water

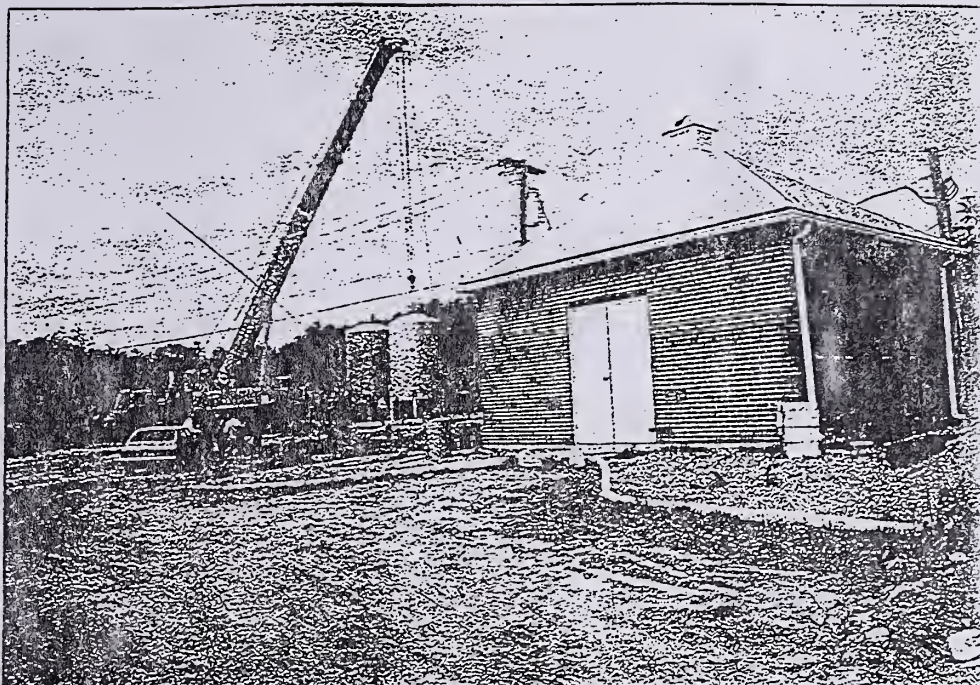
(as possibly affected by suspended solids) was not initially known. The hydraulic surface loading at these locations ranged from 1.0 to 4.5 gpm sq/ft.

At three sites, air stripping was used before carbon adsorption. The purpose of this was to reduce the levels of volatile organic contaminants and allow the carbon adsorption system to act as a final polishing unit.

Also, at six sites the treatment system design included backwashing of the adsorption beds. This feature was incorporated either due to high surface loading rates of 5.7 to 9.6 gpm sq/ft, or for solids removal in certain potable projects.

One of the most critical design parameters for any adsorption system is contact time. This is the length of time that the contaminated water is in intimate contact with the activated carbon. Increasing the depth of carbon for a fixed flow rate or decreasing the flow rate for a fixed depth of carbon both serve to increase contact time.

This important design parameter is generally expressed as *superficial contact time*, or the volume occupied by the activated carbon divided by the water flow rate. The *real contact time* is approximately one-half the superficial. Generally a superficial contact time of 7.5 min. is adequate for treating water that exhibits taste and odor problems. Longer times, however, are usually required as the types of organic compounds in groundwater increase in number and concentration, and approach the mg/l range.



GAC adsorbers destined to treat a municipal water supply are installed at an Acton, Massachusetts site, one of the 31 applications reviewed in this article.

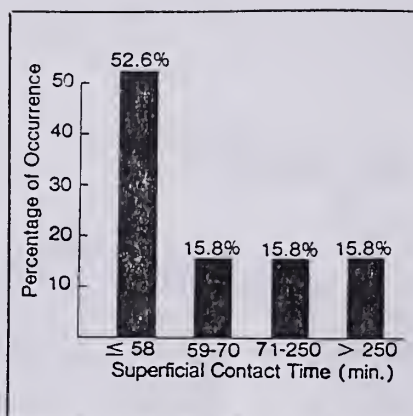


Figure 2. Range of carbon contact times for groundwater treatment projects (mg/l levels).

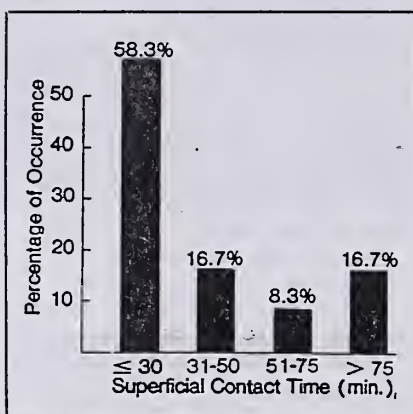


Figure 3. Range of carbon contact times for groundwater treatment projects (ug/l levels.)

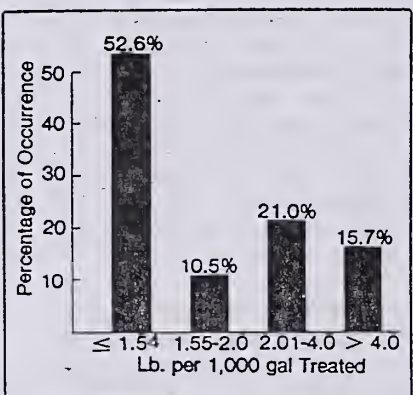


Figure 4. Range of carbon usage for groundwater treatment projects (mg/l levels).

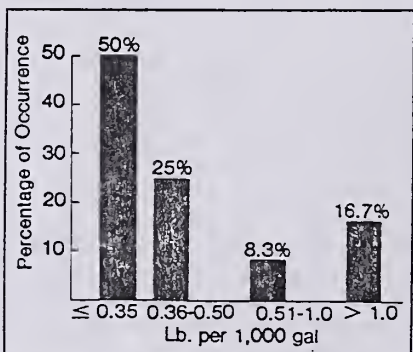


Figure 5. Range of carbon usage for groundwater treatment projects (ug/l levels.)

To improve carbon efficiency where longer contact times are required, two adsorbers are usually connected in series (Fig. 1, page 33). When the effluent from the second, or polishing, bed begins to approach the desired objective, just the first, or lead, bed is removed from service. Removing only completely exhausted carbon in this manner assures maximum carbon efficiency. When placed back on-stream, the second bed becomes the lead and a fresh bed of carbon assumes the polishing position.

Operating conditions and results for those systems treating groundwater with organic contaminants at mg/l levels are displayed in Table 3 (page 34). Of these 19 systems, 16 employed two or more beds in series. Successful treatment was accomplished with total superficial contact time as low as 16 min.

Similarly, Table 4 (page 34) shows the results for those systems treating groundwater with organic contaminants at the ug/l levels. Of these 12 systems, four had two or more beds operated in series and eight had one or more beds in a parallel mode. Successful treatment was accomplished for these systems with total superficial contact time as low as 12 min.

Figures 2 and 3 depict the range of contact times used in the projects as a function of percent occurrence. Fig. 2 reveals that almost 53 percent of the systems treating mg/l levels of contaminants employed a contact time equal to or less than 58 min. In the same manner, Fig. 3 shows that over 58 percent of those processing ug/l levels of contaminants used a contact time equal to or less than 30 min.

Single fixed beds arranged in the parallel mode were installed at the majority of the sites where influent contamination was at ug/l levels, because of the lower contact time requirements. The single fixed bed design provided the advantages of a simple piping network, savings in capital dollars and short installation time. This latter advantage was very important in dealing with emergency situations.

Contact times listed in Tables 3 and 4 were the actual times used at the sites, but they should not be construed as the optimum contact time for removing the particular organic compounds listed. In responding to emergencies such as spills, standard, readily available adsorption equipment was used. Response time and assured performance took precedence over the optimization of contact time in these situations. Thus the contact times used at some sites could have actually provided a substantial margin of safety. A minimum of 12-15 min. contact time is normally recommended for treatment of contaminated groundwater.

Virgin or reactivated carbon was used for all of these projects. Virgin carbon (Filtrisorb 300) was used on the 13 projects where the treated effluent was used for potable purposes. Reactivated carbon was used at the remaining 18 sites where the effluent was either discharged into a receiving stream or re-injected into the related well field.

Activated carbon for organic wastewater treatment can be used on a throw-away basis, reactivated on-site or transported for reactivation off-site. Use of carbon on a throw-away basis can be considered for potable water projects where carbon life is measured in years. On-site reactivation is common on permanent projects where the carbon requirements are large. Most of the carbon used at the 31 treatment sites under study was returned to the company's reactivation facilities. This approach provides both economical carbon reuse and the total destruction of the organic compounds adsorbed on the carbon.

As Table 3 shows, the carbon consumption rates for the contaminant concentrations in the mg/l range varied from 0.45 lb of carbon per 1,000 gal to 13.3 lb of carbon per 1,000 gal. The contaminant concentration varied from 2.0 mg/l to 200 mg/l of organics.

Predictably, the carbon use rate was lower at those sites where the organic contaminants were at the ug/l levels (Table 4). Carbon consumption varied from 0.1 lb of carbon per 1,000 gal to a high of 7.7 lb of carbon per 1,000 gal.

The range of carbon consumption rates as a function of percent occurrence are exhibited in Figures 4 and 5. The former shows that almost 53 percent of the systems handling mg/l levels of contaminants used less than 1.54 lb of virgin carbon for every 1,000 gal of treated water (the median carbon dosage). Figure 5 indicates that 50 percent of those treating ug/l levels of contaminants used less than 0.35 lb of virgin carbon per 1,000 gal. of water.

Operating costs associated with granular activated carbon treatment is dependent on a number of factors. These include flow rates, concentration and type of organics, type of application (potable or other), site requirements, timing requirements, and length of the processing project. These factors together can define equipment, carbon and reactivation needs. Generalizations about costs can be difficult when comparing a variety of applications, but some observations can be made.

As expected, the operating cost for GAC treatment was lower in the case of those projects with lower average influent levels of contaminants. Treatment costs for the situations shown in

Groundwater Contamination

Table 3
Operating Results—Influent Contaminants at mg/l Levels

System No.	Source of Contaminants	Contaminants	Typical Influent Conc. (mg/l)	Typical Effluent Conc. (ug/l)	Flow per Train (gpm)	Surface Loading (gpm/ft²)	Total Contact Time (min.)	Carbon Usage Rate (lb., 1,000 gal.)	Carbon Type	Carbon System Pretreatment	Carbon System Back-Washable	Operating Mode	Disposition of Effluent
1	Truck spill	Methylene chloride 1,1,1-Trichloroethane	21 25	<1.0 <1.0	20	0.25	534	3.9	Reactivated	None	No	2 beds in series	Discharge to surface water
2	Rail car spill	Phenol Orthochloro-phenol	63 100	<1.0 <1.0	80	1.0	201	5.8	Reactivated	Filtration	No	3 beds in series	Discharge to surface water
3	Rail car spill	Phenol Vinylidene chloride	32-40 2-4	<10.0 <10.0	875 Td* 173	2.2	60	2.1	Reactivated	None	No	2 beds in series	Discharge to surface water
4	Rail car spill	Ethyl acrylate	200	<1.0	300 Td* 100	2.0	52	13.3	Reactivated	Filtration	No	3 beds in series	Discharge to surface water
5	Chemical spill	Chloroform Carbon tetrachloride Trichloroethylene Tetrachloroethylene	3.4 130-135 2-3 70	<1.0 <1.0 <1.0 <1.0	40	0.5	262	11.6	Reactivated	None	No	2 beds in series	Process water
6	Chemical spill	Chloroform Carbon tetrachloride Trichloroethylene Tetrachloroethylene	0.8 10.0 0.4 10-20	<1.0 <1.0 <1.0 <1.0	180	2.3	58	2.8	Reactivated	None	No	2 beds in series	Process water
7	On-site storage tanks	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	0.5 1.0 7.0	<1.0 <1.0 <1.0	165	2.1	64	0.8	Virgin FS-300	None	@ installation only	2 beds in series	Process and potable use
8	On-site storage tanks	Methylene chloride 1,1,1-Trichloroethane	1.5 3.3	<100 <1.0	20	0.25	526	4.0	Reactivated	None	No	2 beds in series	Discharge to surface water
9	Chemical spill	Dichloroethyl ether Dichloroisopropyl ether	1.1 0.8	<1.0 <1.0	2250 Td* 750	9.6	16	0.45	Reactivated	None	Yes	2 beds in series	Process and potable use
10	Chemical spill	Benzene Tetrachloroethylene	0.4 4.5	<1.0 <1.0	95	1.21	112	1.9	Reactivated	None	No	2 beds in series	Discharge to surface water
11	Landfill site	TOC Chloroform Carbon tetrachloride Etc., etc.	20 1.4 1.0 14.0	<5.0 mg/l <1.0 <1.0 <1.0	20	1.6	41	1.15	Reactivated	Filtration	No	Dual mini in series	Discharge to surface water
12	Gasoline spill	Benzene Toluene Xylene	9-11 5-7 6-10	<100 Total	5	0.4	214	<1.01	Virgin FS-300	None	No	Dual mini in series	Discharge to surface water
13	On-site storage tanks	Trichloroethylene Xylene Isopropyl alcohol Acetone	3-8 2-5 .2 .1	<1.0 <1.0 <10.0 <10.0	30	2.4	36	1.54	Reactivated	None	No	Dual mini in series	Ground recharge
14	On-site storage tanks	1,1,1-Trichloroethane 1,2 Dichloroethylene Xylene	12 0.5 8.0	<5.0 <1.0 <1.0	200	2.5	52	1.0	V-R	None	No	2 beds in series	Discharge to sewer
15	Chemical spill	DBCP	2.5	<1.0	250	3.2	21	0.7-3.0	Virgin FS-300	Filtration	No	1 bed upflow	Ground recharge
16	On-site well storage tanks	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	0.2 0.5 2.0	<1.0 <1.0 <1.0	150	1.91	70	0.75	Virgin FS-300	None	No	2 beds in series	Process and potable use
17	Chemical by-products	Di-isopropyl methyl phosphonate Dichloropentadiene	1.25 0.45	<50 <10	175	2.2	30	0.7	Reactivated	Filtration	No	1 bed	Groundwater rejection
18	Manufacturing residues	DDT TOC 1,3 Dichloropropene	0.004 9.0 0.01	<0.5 <1.0	160	2.0	31	1.1	Reactivated	Filtration	Yes	1 bed	Discharge to surface water
19	Chemical spill	1,1,1-Trichloroethane Carbon tetrachloride Trichlorotrifluoroethane Tetrachloroethylene	0.42 0.464 5.977 5.800	<10 Each Comp.	200	2.5	53	1.5	Reactivated	None	No	2 beds in series	Discharge to surface water
Median Levels							58	1.54					

This value represents total volume of liquid being treated with granular activated carbon at this site.

Table 4
Operating Results—Influent Contaminants at ug/l Levels

System No.	Source of Contaminants	Contaminants	Typical Influent Conc. (ug/l)	Typical Effluent Conc. (ug/l)	Flow per Train (gpm)	Surface Loading (gpm/ft²)	Total Contact Time (min.)	Carbon Usage Rate (lb., 1,000 gal.)	Carbon Type	Carbon System Pretreatment	Carbon System Back-Washable	Operating Mode	Disposition of Effluent
1	Solvent spill	1,1,1-Trichloroethane Trichloroethylene Tetrachloroethylene	143 8.4 26	<1.0 <1.0 <1.0	350	4.5	15	0.40	Virgin FS-300	None	@ installation only	1 bed	Potable use
2	Gasoline tank leakage	Methyl T-Butyl Ether Di-isopropyl Ether Trichloroethylene	30-35 30-40 50-60	<5.0 <1.0 <1.0	450	5.7	12	0.62	Virgin FS-300	None	Yes	2 beds in parallel	Potable use
3	On-site storage tanks	Chloroform Trichloroethylene	300-500 5-10	<100 <1.0	200	2.5	26	1.19	Virgin FS-300	None	@ installation only	4 beds in parallel	Process and potable use
4	Rail car spill	Chloroform	20	<1.0	30	0.6	160	7.7	Reactivated	Air strip	No	1 bed	Discharge to surface water
5	On-site storage tanks	Trichloroethylene	30-250	<1.0	350	4.5	30	0.16	Virgin FS-300	Filtration air strip	No	2 beds in series	Potable use
6	Chemical solvents	Trichloroethylene Tetrachloroethylene	30-40 140-200	<1.0 <1.0	260	3.3	21	0.21	Virgin FS-300	None	Yes	3 beds in parallel	Potable use
7	Chemical landfill	1,1,1-Trichloroethane 1,1-Dichloroethylene	60-80 5-15	<1.0 <1.0	350	4.5	20	<0.45	Virgin FS-300	None	Yes	2 beds in series	Potable use
8	Gasoline tank leakage	Trichloroethylene Di-isopropyl Ether	40-50 20-30	<1.0 <1.0	450	5.7	12	0.10	Virgin FS-300	Air strip	Yes	2 beds in parallel	Potable use
9	Chemical solvents	Trichloroethylene CIS-1,2-Dichloroethylene	20-25 10-15	<1.0 <1.0	160	2.0	25	<0.22	Virgin FS-300	None	@ installation only	1 bed	Potable use
10	On-site storage tanks	Trichloroethylene	50	<1.0	250	1.6	42	0.38	Virgin FS-300	None	No	2 beds in parallel	Potable use
11	Chemical spill	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	5 5 10	<1.0 <1.0 <1.0	85	1.1	121	0.25	Virgin FS-300	None	No	2 beds in series	Potable use
12	Chemical spill	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	5 5 10	<1.0 <1.0 <1.0	150	1.91	70	0.25	Virgin FS-300	None	No	2 beds in series	Potable use
Median Levels							30	0.25					

Groundwater Contamination

Table 4 (ug/l influent) which were installed on a permanent basis range from approximately \$0.22/1,000 gal to \$0.55/1,000 gal. Operating costs of the facilities covered in Table 3 (mg/l influent) and installed on a permanent basis ranged from \$0.45/1,000 gal to \$2.52/1,000 gal. Figure 6 displays all of these costs in simple graphic form. The level of contamination was reduced to less than detectable levels in each project.

The cost figures listed for the 31 cases include allowances for all the

necessary equipment installation costs, and the supply of granular carbon as required. Cost of treatment with granular carbon is well within the range of

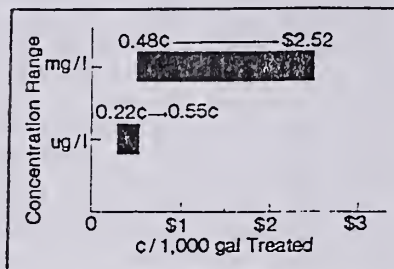


Figure 6. Granular carbon operating costs for groundwater treatment.

conventional treatment processes. Coupled with the fact that GAC can remove a wide range of toxic organics, this data helps show that the granular carbon approach is a cost-effective answer to the recovery and reuse of contaminated groundwater.

Based on these and other experiences in the treatment of industrial and municipal wastewaters with granular carbon, the following observations should be considered in the operation of a groundwater contaminant removal system.

- Some well water supplies could possibly have a high pH and be unstable with respect to the precipitation of calcium salts. pH adjustment of the water, or feeding of a scale inhibitor, may be necessary to prevent precipitation in the lines or carbon adsorbers.

- A monitoring program of the carbon system effluent needs to be established, with trace organic analyses performed on a scheduled basis in order to change the granular carbon at the optimum time.

- Chlorination should follow carbon treatment in those systems where the well water is being used for potable purposes.

In the future, the use of proper hazardous waste disposal techniques will help ensure the preservation of underground water resources. However, the operating results in these full-scale plants have demonstrated that granular activated carbon is an effective and efficient treatment process for removing organic compounds from groundwater supplies that have already become contaminated.

The 31 treatment systems studied and documented have shown that granular activated carbon treatment:

- Reduces a wide range of organic compounds to levels below their detection limits.

- Has been accomplished at remote locations without pre-filtration or backwashing of the carbon beds.

- Has been an effective adsorption process with total superficial contact times as low as 12 min.

- Has achieved carbon usage rates as low as 0.1 lb of carbon per 1,000 gal of water treated.

- Can provide a source of high-quality water at a total operating cost as low as \$0.22/1,000 gal.

About the Authors

Robert P. O'Brien is manager of water quality engineering and J.L. Fisher is water quality engineer, both with the Calgon Carbon Corporation, Pittsburgh, PA. This article is an updated adaptation of a paper read to the Division of Environmental Chemistry, American Chemical Society in Atlanta, GA, March 29-April 3, 1981, by Robert P. O'Brien, David M. Jordan and Walter R. Musser, all of Calgon Corporation.

SITE IDENTIFICATION:

Potable Groundwater Treatment Systems
Del Este Water Company
Modesto, California.

SITE DESCRIPTION:

In July of 1989, the California Department of Health Services (DOHS) lowered the drinking water standard for Dibromochloropropane (DBCP) from 1.0 ppb to 0.2 ppb. As a result of the lowered standard, the Del Este Water Company shut down and removed from service seven production wells.

Faced with the potential of increased water demand in the summer of 1990, Del Este applied and received an amended operating permit to allow use of wells that did not meet the new standard. The permit specified the order in which the wells would be returned to service. Also as part of the permit, Del Este agreed to a timetable for installing well-head treatment systems.

Although Del Este had no intention of using the wells exceeding the new DBCP standards except during severe situations, adverse publicity over the amended permit caused them to accelerate plans for well-head treatment.

Del Este had already determined that alternatives such as drilling new wells or deepening old wells were unacceptable, and that well-head treatment with carbon adsorption was the most viable and cost-effective approach. Del Este Water Company, being a privately-owned utility, also decided that the best procedure was to prequalify and work closely with a single supplier. This qualification was based on background, capability, system quality and based upon events-response capability.

In January 1990, Del Este began to work with Calgon Carbon in developing proposal for and delivery of treatment system. Application of Calgon Carbon's pre-engineered, proven treatment systems facilitated both installation and offered substantive cost savings. Most of the treatment systems would be installed at a total cost of about \$200,000 to Del Este, including all site work and connections.

A purchase order was issued to Calgon Carbon in early March for seven systems (five of which were to be delivered within 30 days, and two within 60 days). All seven well sites were returned to operation in June of 1990, meeting all DOHS water quality standards. Subsequently, an eighth treatment system was installed in Spring of 1991.

SITE IDENTIFICATION:

Potable Groundwater Treatment Systems
Del Este Water Company
Modesto, California

SYSTEM DESIGN PARAMETERS: (basis - individual well)

System Design:	Two (2) adsorbers; series or parallel operation, normally operated in parallel
Adsorber Size:	10-foot diameter x 14-foot straight side (backwashable)
Adsorber Rating:	ASME Code 125 psig at 150°F
GAC Amount & Type:	20,000 pounds Calgon Carbon Filtrasorb 300 per adsorber
Flow:	1000-1500 gpm per well
Contact Time:	9-6 minutes (empty bed or "EBCT" basis)
Contaminants:	Up to 1.4 ppb DBCP (most wells 0.5-0.8 ppb DBCP)
Performance:	DBCP less than 0.02 ppb (or ND)
GAC Usage Rate:	0.04-0.08 lb GAC/1000 gallons (estimated range based on contaminant, flow)
Reference:	Mr. Ken Ward Production Manager Del Este Water Company 430 Tenth Street Modesto, CA 95353 (209) 522-1073

SITE IDENTIFICATION:

Temporary Granular Activated Carbon Water Treatment System
City of St. Anthony
St. Anthony, Minnesota

SITE DESCRIPTION:

In 1988, Calgon Carbon Corporation provided a complete adsorption system to treat contaminated potable groundwater for the City of St. Anthony. The system was provided to St. Anthony on a temporary basis, to operate for an expected 500 days, or until a permanent treatment facility could be installed and operational.

The system consisted of 4 adsorbers to be operated in parallel. The system was designed to treat up to 2,400 gpm at a total system pressure drop of less than 15 psig. The adsorption system was to reduce volatile organic compounds (VOCs) in the influent, consisting of 1,2 dichloroethylene, trichloroethylene and other chlorinated aliphatics, from levels of up to 35 ug/l to less than 1 ug/l.

The treatment system consisted of ASME coded, 75 psig lined steel adsorbers, all steel piping with butterfly valves for flow control, and all other auxiliary piping and instruments to comprise a complete treatment system. Calgon Carbon Corporation was responsible for the installation of the adsorption system including initial fill of 80,000 lb. GAC and start-up of system.

In early 1988, upon finding VOC contamination in the potable groundwater, St. Anthony contracted with Rieke Carroll Muller Associates (RCM) of Minnetonka, Minnesota to develop a specification for a temporary treatment system. This specification called for suppliers to bid on installation, service fee and tear down for the temporary equipment, as well as a fee for each pound of VOC removed by the system.

Calgon Carbon bid the treatment service on May 18th and was awarded the contract on June 3. In approximately 30 days, as required by the contract, the treatment system was installed, filled with GAC and ready for operation.

The system operated until June 20, 1989 when contaminants were detected at 0.2 ug/l. At this time, the treatment system had treated 536 million gallons, for a carbon usage of 0.15 lb/1000 gallons.

The temporary treatment system is expected to remain on-line until September 1, 1990, at which time a permanent carbon adsorption treatment facility will be installed (and operational in 1991).

In the course of the contract with the City of St. Anthony, Calgon Carbon Corporation provided all payment and performance bonds, certificates for the labor rates, affirmative action and equal opportunity required for municipal/government agency contracts.

SYSTEM DESIGN PARAMETERS:

System Design	:	4 Adsorbers, Parallel Operation
Adsorber Size	:	10 ft. diameter x 10 ft. side
GAC Amount & Type	:	20,000 lb. Calgon Carbon Filtrisorb 300 per adsorber
Flow	:	2400 gpm (600 gpm per adsorber)
Contact Time	:	9 minutes (empty bed or 'EBCT' basis)
Contaminants	:	VOCs (Dichloroethylene, trichloroethylene, etc.) up to 35 ppb total
Performance	:	VOCs to less than 1 ppb
GAC Usage Rate	:	0.14 lbs/1000 gallons, actual
Reference	:	Mr. Charles S. Barger P.E. Project Manager Rieke Carroll Muller Assoc., Inc. 10901 Red Circle Drive Minnetonka, MN 55343 612-935-6901 Mr. Larry Hamer City of St. Anthony 3301 Silver Lake Road St. Anthony, MN 55418 612-789-8881

Activated Carbon Treatment Restores Acton Water Supply

District lost one million gallons of water per day, 40 percent of its water supply, when two wells were found chemically contaminated.

By John E. MacLeod and George R. Allan

Many New England municipalities have traditionally taken pride in the fact that water from their gravel-packed wells requires no treatment. Some do not even require chlorination. Unfortunately, the purity of these suppliers has led some communities to place too much faith in nature's ability to protect the quality of their groundwater.

During the past four years, the closing of more than two dozen public water supplies in Massachusetts has demonstrated the susceptibility of groundwater to contamination. One of the first communities to be affected was Acton, a town 22 miles west of Boston.

Acton's water district lost one million gallons per day (mgd), 40 percent of its water supply, in December 1978 when two wells were taken out of service after several organic chemicals — including trichloroethylene, dichloroethylene, methylene chloride, and benzene — were detected. The district removed the wells from service until the source and toxicity of the contaminants could be resolved.

The two wells — Assabet No. 1 and Assabet No. 2 — are in the Sinking Pond aquifer, which encompasses approximately 375 acres. Sixty-five of the acres are owned by the water district. More than 100 test wells penetrated the aquifer's sand and gravel overburden during various investigations, making it one of the most studied aquifers in Massachusetts.

The municipal wells each have a yield of 0.5 mgd. During 1978, their average total monthly withdrawal was 17 million gallons. In addition to these two wells, the aquifer is the site of three industrial wells, pumping an average of 11 million gallons per month. This water is used for industrial cooling, and is then recycled back into the aquifer.

A year-long hydrogeological study conducted of the Sinking Pond aquifer

in 1979 determined the probable cause of contamination to be the waste disposal practices of a nearby chemical plant. The primary sources were a landfill and several lagoons filled with liquid wastes, located approximately 2,500-3,000 feet north of the municipal wells. The groundwater gradient across the aquifer slopes from north to south.

The study also delineated an extensive plume of contamination extending to within 1,000 feet of Assabet No. 2, the well closest to the chemical plant. Concentrations of total chlorinated hydrocarbons in this contaminated plume were as high as 10,000 parts per billion.

With the need for immediate action to meet the water needs of its customers, the district took the following approach to the problem:

- banned the use of outside water, prohibiting such activities as lawn watering and car washing;
- initiated public education programs promoting water conservation;
- installed a booster pumping station to draw water from the neighboring town of Concord; and
- initiated a maintenance program to improve the efficiency of the remaining active wells.

The success of these short-term programs enabled the water commissioners to concentrate on two long-term goals: obtaining additional permanent water supplies, and restoring the Assabet wells to usable conditions.

The first step toward achieving the goals was increasing funding for water supply investigations from the previous \$15,000 annual appropriation to a range of \$75,000 to \$100,000 per year.

Investigators located three sites producing satisfactory test results. The sites

Acton used two granular activated carbon treatment tanks to help restore its wellwater quality.



have an estimated combined safe yield of 1.0 mgd. The wells are in North Acton, about two miles from the existing distribution system. The district is proceeding with the acquisition of approximately 65 acres at the three sites.

The board of water commissioners also took other actions to ensure an adequate water supply. The board obtained voter approval to fund a town-wide hydrogeological study to assist in the management and protection of current and future water source supplies. A five-member land-water management advisory committee was appointed to

assist the board in studying the problems facing the district.

The district then began investigating possible treatments for the Assabet wells. The first step was building a pilot plant that treated water from Assabet No. 2, the well with the higher level of contaminants. The plant used granular activated carbon (GAC) with and without aeration to treat the water. The investigation, which continued through the second half of 1979, indicated the GAC and aeration were effective in removing the chlorinated hydrocarbons from the aquifer.

During 1980, the water commissioners' attention focused on the legal aspects of the contamination. In April, the federal Environmental Protection Agency filed suit against the chemical company, demanding it "remove, neutralize, or isolate all chemical wastes and contaminated soil" on its property. This was the first suit filed in Massachusetts under the federal Resource Conservation and Recovery Act.

Six months later, the suit was settled out of court by a consent decree under which the company agreed to develop a plan to clean up the aquifer and restore it to usable conditions. The water district was not a party in the EPA suit.

However, in October 1980, the commissioners filed a \$3 million suit against the chemical company based on the loss of the two public water sources and the contamination of the aquifer. The suit is pending in federal court.

During the summer of 1981, the district stepped up efforts to treat the Assabet wells. Representatives of the Calgon Corp., of Pittsburgh, Pennsylvania, explained the use of granular activated carbon for removing organic contaminants from groundwater.

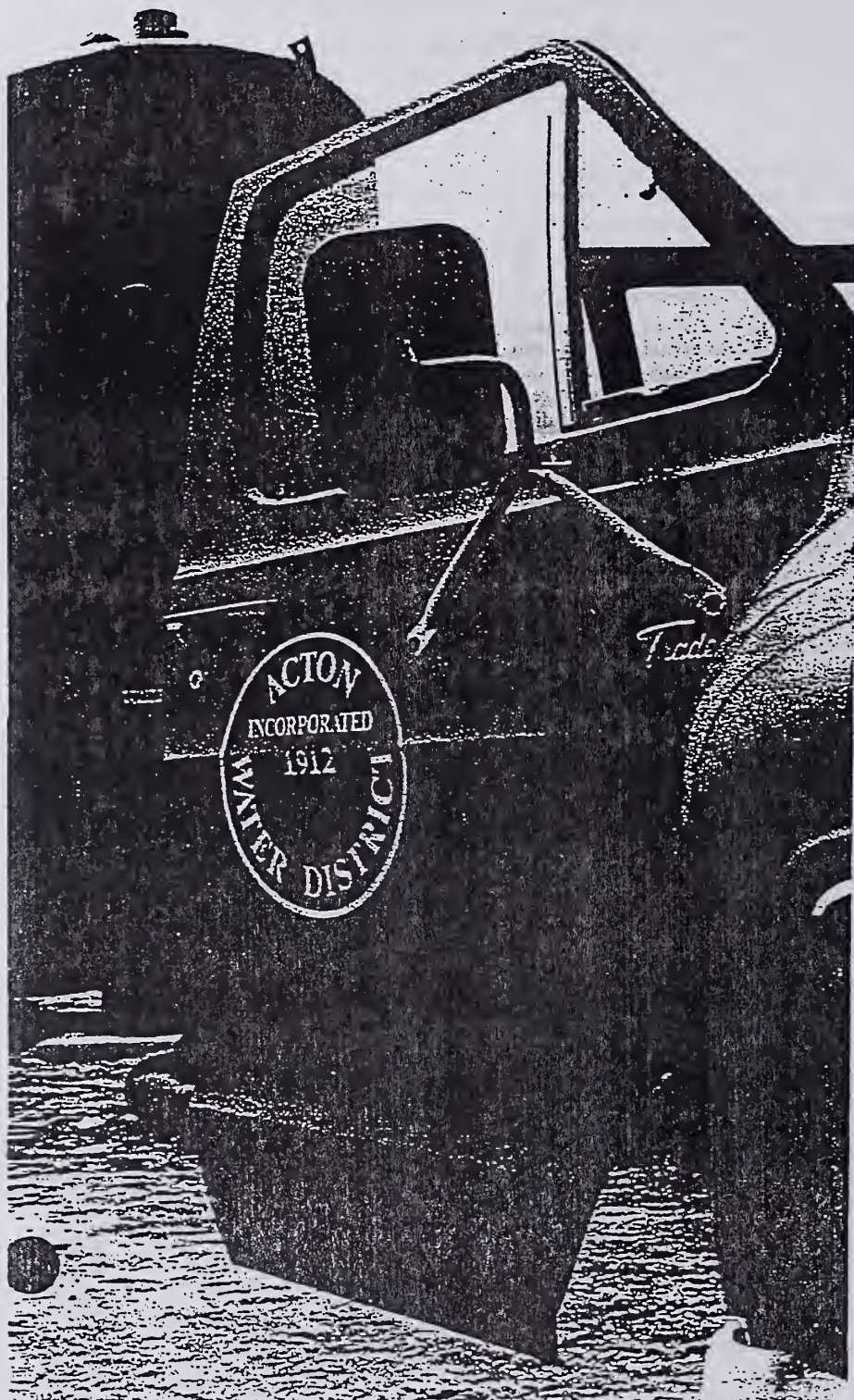
Calgon Corp. conducted an accelerated column test in the fall of 1981, showing that carbon treatment would remove volatile organics to less than detectable levels—less than one part per billion. Calgon proposed a full-scale, pilot-plant trial to determine carbon exhaustion rates under actual field conditions. The study permitted the evaluation of the adsorption rates of volatile organics under varying concentrations, while providing the district with 0.5 mgd of water.

The district's March 1982 annual meeting appropriated \$200,000 to fund the full-scale pilot plant. The chemical company offered to contribute \$100,000 of the expense, which the district accepted.

The full-scale pilot plant was designed to treat the 0.5 mgd from Assabet No. 1. Calgon was the successful bidder to furnish two adsorbers and 40,000 pounds of GAC. Water district personnel installed the adsorbers and interconnecting piping in a manner allowing the treatment of the Assabet wells.

The two adsorbers were piped in series. This permitted evaluation of the GAC exhaustion rate in the first adsorber, while the second continued to polish the effluent.

The district established a criterion for the treated water: a maximum total volatile organics content of 5.0 parts per billion. To monitor the quality, an extensive sampling and testing program was adopted. Not only was this carried out by the Massachusetts Department of



The Cost of Acton's GAC Treatment

Installation cost

Foundation and site work	\$ 5,500
Piping (material only; labor by district employees)	20,000
Crane rental	1,100
Calgon set-up (including activated carbon)	60,400
Miscellaneous (chemical feeder, alarms, fence, etc.)	6,400

Total \$93,400

Monthly operating cost

Calgon rental	\$ 4,945
Electricity for well pump	1,800
Sampling and testing	2,000

Total \$ 8,745

water district's standard of 5.0 parts per billion for total volatile organics were not measured in the effluent from the first adsorber until after 27 weeks of continuous use. During this period, the GAC in the adsorber had treated a total of 88 million gallons of water.

The average influent concentrations of trichloroethane and dichloroethylene were 40 parts per billion and 1.5 parts per billion, respectively. Under these conditions, carbon usage at the pilot plant was 0.34 pounds per 1,000 gallons of treated water.

Final treatment costs cannot be established until the raw water quality stabilizes. Factors affecting the cost of treating water with GAC include the types and concentrations of contaminants in the influent, the flow rate, and the effluent criteria.

This pilot plant demonstrated GAC could effectively remove contaminants in the concentrations found in the Sinking Pond aquifer.

Yet, raw water contamination levels continued to increase. The district evaluated air stripping in packed towers as a pretreatment to extend the life of the GAC. In early 1983, the district voted to make a carbon installation permanent, and to develop and install an aeration system. In addition, the district appropriated \$11,000 to purchase a portable gas chromatograph. This instrument will augment the present sampling program and monitor water quality at other wells.

Acton's approach to combat contamination and manage groundwater resources is a model for communities facing similar problems. Until now, financial considerations usually prompted municipalities to seek alternative water sources instead of treating contaminated existing supplies. Acton's experience has demonstrated that treating water contaminated by volatile organics is an economical and viable procedure. □

John E. MacLeod is district manager of the Acton Water District. George R. Allan is vice president of the consulting firm of Dufresne Henry, Inc.

Environmental Quality Engineering and the federal EPA, but three private firms also were employed for the task. At least two labs performed analyses on samples taken weekly from the influent, the effluent from each of the adsorbers, and samples from several outlying monitoring wells.

Construction started in May 1982 and, by June, water from Assabet No. 1 was pumped through the adsorbers. During the first two weeks the system was in operation, the effluent was discharged into the Sinking Pond aquifer. After laboratory testing confirmed the treated water's purity, approval was granted in July 1982 to put Assabet No. 1 back into the municipal system—after its 3½-year absence. Now, the water is fluoridated prior to GAC treatment and, after treatment, is chlorinated to a 0.25 mg/L residual.

Early tests showed the raw water pumped from the well did not contain any detectable level of volatile organic

contaminants. This was expected, because the normal groundwater flow pattern in the aquifer under non-pumping conditions would carry the plume of contamination past this well. Pumping, however, was expected to eventually draw contaminated water into the well. A second reason for the lack of measurable contamination was the intercepting effect of the pumping of Assabet No. 2, which was being piped to Sinking Pond by the chemical company as part of its pumping test of the aquifer.

After one month of pumping, the first chlorinated hydrocarbons were detected in the raw water. The two primary contaminants were 1,1,1 trichloroethane and 1,1 dichloroethylene. Contaminant concentrations continued to increase for the testing duration, reaching a level in excess of 150 parts per billion.

Contamination levels exceeding the

SUFFOLK COUNTY WATER AUTHORITY, OAKDALE, LONG ISLAND, NEW YORK

The water authority has a lengthy reliance on well water. In recent time many wells have become contaminated with agricultural chemicals, petrochemicals and chlorinated solvents. Until 1988, the water authority's experience using granular activated carbon treatment was limited. Small carbon units had been placed at individual homes to remove agricultural chemicals such as Temik and Aldicarb. Larger granular activated carbon adsorption units had been installed at the Dix Hills, Southold and Greenport wells.

In 1985, Calgon Carbon Corporation provided a single adsorber activated carbon system at the Oakdale well. Starting in 1988, the Water Authority began consolidating their treatment program anticipating the January, 1989, New York State standards. The Authority issued a request for bids for 125 psig paired adsorbers with the capability to operate pairs in series (700 gpm @ 15 minute contact time) or parallel flow (1,000 gpm @ 10 minutes contact time), each adsorber 10 foot diameter containing 20,000 pounds of Filtrasorb 300 granular activated carbon.

Well contaminants were primarily chlorinated solvents being less than 20 ppb (max) and the effluent treatment requirements were established at less than 5 ppb of VOC's. The April 4, 1988 bid date found Calgon Carbon Corporation as the responsive, qualified bidder and the corporation was awarded a contract to supply five (5) dual adsorption systems. With the satisfactory performance of this phase of the project completed, the Suffolk County Water Authority placed an order in August, 1988 for an additional 33 dual adsorption systems. Some of the contaminated well locations required the installation of two adsorption systems to treat 2,000 gpm. At this point in time, the Suffolk County Water Authority became Calgon Carbon Corporation's largest single customer of adsorption equipment.

A third phase to the project was implemented adding 20 additional dual adsorption systems increasing the project requirements to 58 dual adsorption systems with each system sized to treat 1,000 gpm. Most sites experience a carbon use rate of < 0.04#/1,000 gallons allowing a one year bed life.

Suffolk County renewed the supply contract with Calgon Carbon Corporation which included carbon exchange services. In 1990, the contract was rebid and once again Calgon Carbon Corporation was the successful bidder.

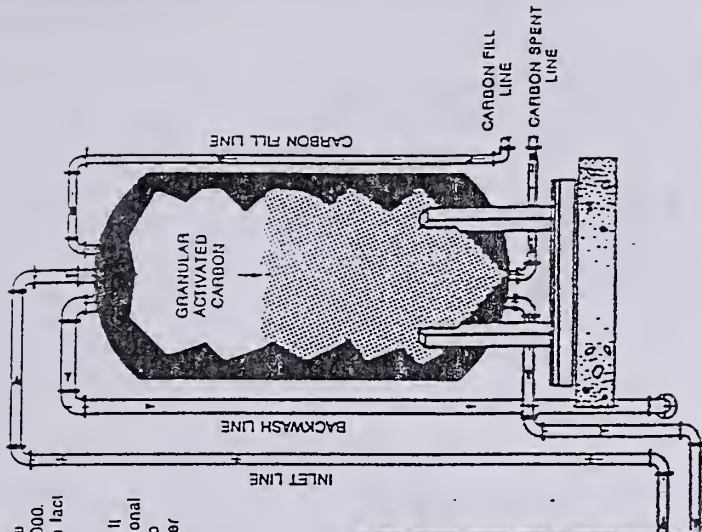
CONTACT: Mr. Ed J. Rosavitch, P.E., Chief Engineer, Suffolk County Water Authority, Sunrise Highway at Pond Road, Oakdale, New York, 11769, 516-589-5200.

Well Restoration Program Implemented to Meet 1989 Water Standards

As of January, 1989, new water standards promulgated by the New York State Department of Health went into effect. The new standard of two (5) parts per billion for virtually all synthetic volatile organic chemicals is an extremely stringent regulation that surpasses the drinking water standards of any other state in the U.S.A.

In order to comply with the new standards, the Water Authority has implemented a remediation program utilizing Granular Activated Carbon Systems (GAC's). Since January 1989, the Water Authority has installed thirty-six (36) GAC's for those wells that had to be removed from service due to volatile organic chemicals and/or pesticides. Ten (10)

of these filters were installed in this fiscal year. Each GAC costs approximately \$500,000 which includes the installation and housing of the unit. The approximate cost of this program to date is \$18,000,000. This is a staggering amount of money in view of the fact that there are no governmental funds available to mitigate against the impact of these regulations. Implementation of this program was quite a task. It took a monumental effort on the part of our professional staff and the outcome was outstanding. Because the Authority moved swiftly and decisively, we have never contravened the new standards.



GRANULAR ACTIVATED CARBON SYSTEM

The Granular Activated Carbon System (GAC) is used for the efficient removal of dissolved organic compounds from water intended for potable use. A unit consists of two process vessels. Each vessel contains 20,000 lbs. of Granulated Activated Carbon. When the carbon in the vessels becomes saturated with contaminants from the water, the unit is shut down and the spent carbon is replaced.



All our GAC systems will be enclosed in attractive buildings to prevent freezing, reduce maintenance, and blend in with the neighborhood.

Table 5
CASE STUDIES

TREATING GROUNDWATER FOR POTABLE WATER USE
INFLUENT CONTAMINANTS AT $\mu\text{g/l}$ LEVELS
CARBON: CALGON FILTRASORB 300 (VIRGIN GRADE)

System No.	Contaminants	Typical Influent Conc. ($\mu\text{g/l}$)	Typical Effluent Conc. ($\mu\text{g/l}$)	Surface Loading ($\text{gpm}/\text{ft.}^2$)	Total Contact Time (Min.)	Carbon Usage Rate ($\text{lb.}/1000 \text{ Gal.}$)	Operating Mode
1	1,1,1-trichloroethane Trichloroethylene Tetrachloroethylene	143 8.4 26	< 1 < 1 < 1	4.5	15	0.4	Single Fixed Bed
2	Methyl T-Butyl Ether Di-Isopropyl Ether	30 35	< 5 < 1	5.7	12	0.62	2 - Single Fixed Beds
3	Chloroform Trichloroethylene	400 10	< 100 < 1	2.5	26	1.19	4 - Single Fixed Beds
4	Trichloroethylene Tetrachloroethylene	35 170	< 1 < 1	3.3	21	0.21	3 - Single Fixed Beds
5	1,1,1-Trichloroethane 1,1-Dichloroethylene	70 10	< 1 < 1	4.5	30	0.45	Two Fixed Beds in Series
6	Trichloroethylene Cis-1,2-Dichloroethylene	25 15	< 1 < 1	2.0	35	0.32	Single Fixed Bed
7	Trichloroethylene	50	< 1	1.6	42	0.38	2 - Single Fixed Beds
8	Cis-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	5 5 10	< 1 < 1 < 1	1.91	70	0.25	Two Fixed Beds in Series

Source: "There is an Answer to Groundwater Contamination" by Robert O'Brien and J. L. Fisher; Water/Engineering & Management, May, 1983.

GRANULAR ACTIVATED CARBON ADSORPTION FOR
VOC REMOVAL FROM DRINKING WATER SUPPLIES

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Marketing Manager

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INTRODUCTION

The recent amendments to the Safe Drinking Water Act (SDWA) have generated increased interest in evaluating a number of different technologies for the removal of Volatile Organic Contaminants (VOCs) from drinking water supplies. Since 1974, the EPA has generated Maximum Contaminant Levels (MCLs) for 26 contaminants, but the new amendments have called for accelerated regulation by requiring development of MCLs for 83 specific contaminants. Many of these contaminants are VOCs which have been discovered in groundwater sources for drinking water supplies. Of immediate concern are the 8 VOCs that are set for regulation in 1987, shown with their proposed MCLs in Table 1 (1).

The use of granular activated carbon (GAC) to remove organic contaminants by adsorption on the large internal surface area of the activated carbon granule has long been a proven and established technology. Over 150 public drinking water systems already have experience with GAC in the removal of taste and odor causing organic compounds in the United States and over 200 in Europe (2). Many industrial plants have also used GAC for the removal of specific organic compounds from water, wastewater and chemical products. Recently, GAC has been used to remove specific VOCs from groundwater or contaminated water resulting from accidental spills (3).

The success of GAC in removing organic contaminants from water has resulted in the amendment to the SDWA establishing GAC as the "yardstick" by which other treatment technologies are to be evaluated in the control of synthetic organic chemicals (4). Other treatment techniques must be at least as effective as GAC in order to be considered viable. Although often perceived as an expensive treatment technology, GAC can often be the most cost-effective solution to the problem at hand. What is needed is a reliable method to evaluate the applicability of adsorption and to estimate the cost to the water system operator.

This paper will present a methodology by which GAC can be evaluated, starting with isotherms for preliminary evaluation and continuing on to parameters for system design. The design of the GAC system will provide capital expenditure guidelines, while the evaluation procedure

should provide a good estimate of the ongoing operating costs.

PRELIMINARY EVALUATION: ISOTHERM TESTING

The liquid phase adsorption isotherm test is the basic preliminary evaluation technique for activated carbon treatment. The adsorption isotherm is a batch test designed to determine the equilibrium relationship between the contaminant in the liquid, measured as concentration, and the contaminant adsorbed on the activated carbon, expressed as carbon capacity or weight of contaminant per unit weight of activated carbon.

The application of the isotherm test to evaluate adsorption of VOCs has historically resulted in unreliable and disparate data. In response to the need for reliable evaluation data, an isotherm procedure has been developed which minimizes analytical errors and more accurately predicts adsorption capacity of GAC for VOCs. This procedure includes handling samples while allowing no head space, using relatively large quantities of powdered activated carbon to minimize weighing errors, and using relatively large initial concentrations of VOCs to minimize analytical errors and provide reliable data points at the higher concentrations to better fix the isotherm plot.

The isotherm test conditions are summarized in Figure 1. The activated carbon used is Calgon Carbon's Filtrasorb 300, a bituminous coal based activated carbon with a high surface area ($1000 \text{ m}^2/\text{gm}$) and Iodine Number (typically 970). The activated carbon is pulverized to -325 mesh to eliminate the diffusion rate as a factor. The water samples consist of reagent grade chemicals added to purified water. As shown in Figure 1, the activated carbon dosages result in the development of low level VOC equilibrium concentrations which are useful for evaluation. The sealed flasks are agitated for a minimum of 20 hours to assure equilibrium. The contents are then pressure filtered through 0.45 micron filter pads, with the filtrates analyzed by gas chromatography using the purge and trap technique with the amount of the compound retained on the activated carbon calculated by difference.

In 1984, results from single component isotherms of five of the more common chlorinated solvents were presented (5). Single component isotherms from eight more VOCs have been conducted to expand this data base. It is most important to note that when comparing the relative adsorbability of one compound to another, and especially when adding consideration of concentration effects, that the testing protocol be consistent. Therefore, it is anticipated that this data base of isotherm tests will be useful in determining effects of contaminant and concentration changes possible in long term groundwater treatment.

All thirteen isotherms are presented here for reference.

Figure 2 shows the results of isotherms for seven of the VOCs due for regulation in 1987. The eighth VOC, vinyl chloride, is normally a gas at ambient temperature, and has a very low capacity on GAC in liquid phase adsorption. Investigations into the removal of vinyl chloride by activated carbon have reported poor capacities. However, vinyl chloride removal by aeration has produced good removal efficiencies (7). The isotherm results for p-dichlorobenzene are from earlier test results using less agitation time, but p-dichlorobenzene is well adsorbed by activated carbon and the results are consistent with recent tests.

Figure 3 has grouped the remaining chlorinated and brominated aliphatic solvents and Figure 4 the aromatic and chlorinated aromatic solvents. The isotherms point out characteristics useful for considering adsorption of other compounds; i.e., that the capacity of activated carbon for the contaminant increases with concentration, molecular weight and decreasing solubility of the contaminant.

Isotherms are useful in identifying whether a compound is amenable to adsorption by activated carbon. The test indicates the theoretical capacity for these contaminants by GAC, which as will be shown later, allows the development of estimates of carbon usage rates for cases where a single contaminant predominates. Care must be taken in using these single component isotherms when the contamination involves a mixture of adsorbable compounds. Although these isotherms might allow for preliminary estimates of activated carbon usage rates, additional testing would be warranted to establish more reliable carbon usage rates. Finally, background organic contaminants, usually more prevalent in surface water than groundwater, may cause reduced capacity. Isotherms performed on a specific water according to these procedures would provide for good comparison to these single component isotherms and a basis for estimating GAC usage rates.

After a column study is performed or actual operating data is obtained, isotherms are useful in evaluating effects of concentration or contaminant change. A relationship can be established between the actual usage rate and the equilibrium data of the isotherm, and changes in usage rate can be predicted using the isotherms as reference points.

ADVANCED EVALUATION: ACCELERATED COLUMN TESTING

The effect of short contact times experienced in actual operation and the accurate prediction of activated carbon usage rates is normally obtained in the scaled column study. The accepted test method for the column study has been to use the GAC in columns sized from 1 to 4 inches in diameter, and with selection of surface loading rates and media depth, obtain the desired empty bed contact times in single or multiple columns. The low usage rates expected

in groundwater treatment to remove low levels of VOCs often make a directly scaled study infeasible due to the time and analytical expense involved.

Several researchers have explored the possibility of small rapid column tests (6). The basic principle is to use smaller size granules of the same activated carbon, but with high surface loading rates and short contact times. Using mathematical models of basic adsorption kinetics, these rapid column tests can then be used to predict full size system performance. Calgon Carbon Corporation has developed a high pressure mini-column technique, the Accelerated Column Test (ACT), which uses 50 mg of Filtrasorb 300 grade GAC that has been sized to less than 100 mesh in a column with an internal diameter of 1.94 mm (7). The ACT procedure has been tested in comparison with one inch diameter column studies and existing full scale systems with the results showing a high degree of correlation (8).

The ACT can be used, as mentioned previously, to model the performance of a particular system in order to fix contact times and predict usage rates and breakthrough characteristics. Historical ACT data can also be used to predict performance on potential applications. In this procedure, ACT data can be compared to isotherm data to determine how much of the theoretical capacity can be realized under dynamic conditions. As when comparing isotherm results, these ACT's need to be performed under similar conditions with the same mathematical scale-up model to assure consistency.

PREDICTION OF USAGE RATES WITH ACT AND ISOTHERM DATA

We have performed numerous ACT studies on waters contaminated with low levels of VOCs. These studies can be reviewed to determine how much of the equilibrium capacity identified in the isotherm test can be realized in an operating system.

Table 2 shows the results of ACTs run on actual and synthetic groundwater samples containing essentially a single VOC. Both the synthetic and actual samples used waters with low (<0.5 ppm TOC) background of organic compounds. These tests show that operating systems with short contact times can generally obtain 45-55% of the theoretical capacity of the activated carbon at breakthrough of the contaminant. Besides indicating that a predictable amount of capacity can be obtained, these tests indicate a relatively short adsorption zone in the bed, and that upon breakthrough little adsorptive capacity remains. Results of this testing suggests that contact times of 12-15 minutes be used to optimize activated carbon usage and that single stage adsorption systems be employed to minimize capital costs in designing systems to remove low levels of VOCs.

Table 3 shows results of ACTs run on actual groundwaters including results from other commonly encountered

situations. The first site shows the effect of higher contaminant levels of a well adsorbed VOC. With higher levels of trichloroethylene (TCE) and slightly greater than 15 minutes contact time, the ACT predicts a 68% attainment of the equilibrium isotherm data. This result indicates that in the adsorption process, the higher concentration contaminant acts as a greater driving force towards equilibrium capacity.

The second site investigated shows the influence of background organic contaminants on the adsorption of chlorinated solvents. A municipal drinking water containing 135 ppb of chloroform that also contained 6 ppm background organic contamination measured as TOC was tested. The ACT indicated that the presence of this organic background resulted in only 37% of the theoretical capacity being achieved. This capacity is approximately 20% less than the capacity achieved in the municipal drinking water sample shown on Table 2.

The third site in this set shows the effects of a mixture of VOCs; 1,1,1 trichloroethane (TCA) and TCE. As shown in the isotherm data in Figure 2, the TCA is not adsorbed as strongly, so it is expected to break through first. The column study did indicate that the TCA was detected first in the effluent, and the capacity of carbon for TCA was only 34.3% of its equilibrium value. Another way of looking at this mix is that at an equilibrium capacity of 3.5 mg/gm and 55 ppb of TCA, the theoretical usage rate would be 0.13 lbs. GAC per thousand gallons. This usage rate can be added to a usage rate of 0.06 lbs. GAC/1000 gallons for TCE (24 mg/gm at 165 ppb) for a total usage rate of 0.19 lbs. GAC/1000 gallons for both contaminants. The actual usage rate is approximately 58% greater than the theoretical, indicating a working capacity that realizes approximately 63% of the equilibrium capacity.

In considering these ACT studies on VOC removal, it can be concluded that for low level VOC contamination in waters containing low background TOC, operating activated carbon adsorption systems can achieve 45-55% of the theoretical isotherm capacity. When the chemistry becomes more complex, with background TOC or the presence of a mixture of contaminants, a simple rapid mini-column technique can be conducted to explore these additional effects.

ADSORPTION SYSTEM DESIGN AND ECONOMICS

Based upon the evaluation procedure discussed above, the investigator can proceed with preliminary system design and establish the economics for activated carbon treatment. It was shown earlier that for waters with one or two VOCs present at low levels - 200 ppb or less, contact times of 12 to 15 minutes are acceptable. Also, for these conditions, and especially if only a single VOC is present, the mass transfer zone is sufficiently short that a single stage adsorption system can usually achieve optimum economic utilization of the activated carbon. The use of single stage systems rather than multiple stages

will minimize costs for the treatment equipment. A simple in-bed sample port can be utilized to anticipate contaminant breakthrough and provide an added safety factor for effluent quality.

The use of single stage systems allows the use of GAC as substitute media in sand filters, if these are already in position at the treatment facility. At a 2 gpm per square foot loading rate, a 4 ft. deep bed of GAC will provide 15 minutes of contact time. Other investigators have reported that GAC is also an adequate replacement for most media in performing required filtration (2). In such a case, there is no major capital expenditure for additional equipment.

For most groundwater treatment applications, however, it is more likely that a treatment unit would be required between the groundwater well pump and the distribution system. In this case, a single stage pressure adsorber can be placed in-line to provide treatment without repumping. Typically, 10 ft. diameter adsorption vessels containing 20,000 lbs. of GAC are used for this service. Adsorption vessels with 20,000 lbs. of GAC have become a standard size unit, as the spent GAC from a single unit can be transported from the site for spent carbon handling in a single over-the-road trailer. The limitation is due to weight considerations, as the entire quantity of GAC, retained moisture and adsorbate will weigh approximately 40,000 pounds. Each of these units can treat 350 gpm and provide a contact time of 15 minutes. The adsorption process, operated in a downflow mode, will typically add a 15 psig pressure drop to the system.

Each single adsorber as described above, complete with process, utility and carbon transfer piping can be installed on an existing foundation for approximately \$75,000. This cost would not include other portions of the overall installation, such as foundations, pump work or tie-in to the existing system.

The following example illustrates the methodology that can be applied to obtain preliminary economics for a groundwater treatment scenario. The conditions that can exist at a groundwater sourced drinking water supply are:

Flow: 600 gpm (0.864 mgd)
Contaminant: Trichloroethylene
Concentration: 180 ug/l (ppb)
TCE MCL: 5 ug/l
Background TOC Level: Negligible (<1 ppm)

Based upon the evaluation information provided, the following design assumptions can be made:

Adsorber Size: 10 ft. dia., 20,000 lbs. GAC
Adsorber Quantity: Two Units
Contact Time: 17 minutes
Equilibrium Capacity: 25 mg TCE/gm GAC (Figure 1)
% Eq. Capacity Realized: 50% (Table 2; estimate)

Estimated Capacity: 12.5 mg TCE/gm GAC
Estimated GAC Usage: 0.12 lbs./1000 gallons
Estimated Annual GAC Usage: 40,000 lbs.

To predict the operating cost, an estimate is made for the installation of the adsorption system as shown in Table 4, resulting in a total installed capital expenditure of approximately \$250,000. In some geographical areas, freeze protection such as insulation with heat tracing, or a building, may also be necessary.

Finally, the annualized operating cost for the adsorption system can be estimated by amortization of the capital expenditure and addition of the expenses as shown in Table 5. The unit cost for the treatment system under consideration can therefore be estimated to be 27 cents for each 1000 gallons treated. This figure is consistent with a value of 34 cents per 1000 gallons estimated by the EPA for systems below 1 mgd and for 99% removal of TCE up to 500 ppb (9).

CONCLUSION

The recent interest in technologies for treatment of waters contaminated with low levels of VOCs has increased the need for reliable data bases to be used for preliminary evaluation. This need is especially critical in the evaluation of activated carbon adsorption, which is regarded as the basis by which other technologies are measured.

The adsorption isotherm is the basic evaluative tool for activated carbon adsorption, and can be an effective predictor for activated carbon usage rates when combined with reliable dynamic studies. For the isotherms presented in this paper, care was taken to minimize analytical errors and assure equilibrium conditions. As a result, this series of isotherms can be compared to each other and used as a reliable point of reference for column studies. Finally, rapid mini-column tests similar to the Accelerated Column Test can be used to effectively model full scale systems.

Results discussed here indicate that for groundwaters contaminated with essentially a single VOC at low levels with little background organic contaminants, 45-55% of the equilibrium capacity can be obtained using contact times of 12 to 15 minutes. The short mass transfer zones also indicate that single stage adsorbers can be employed to minimize capital expenditures.

The methodology exists then, to properly evaluate activated carbon treatment for both performance operation and costs. This procedure will be helpful as a point of reference to evaluate other treatment technologies and as a planning technique for the employment of activated carbon adsorption.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of the Research and Development Group of Calgon Carbon Corporation for their consistent efforts in testing and analysis: Mr. Joseph Bellissimo, Ms. Diane Galicic and Mr. Dave McNamara for isotherm and ACT testing, and Ms. Pat Reiser for VOC analysis.

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FIGURE 3
ACTIVATED CARBON ADSORPTION ISOTHERMS
CHLORINATED SOLVENTS

- | | |
|------------------------------|------------------------|
| (1) Tetrachloroethylene | (4) Chloroform |
| (2) Trichloroethylene | (5) 1,2 Dichloroethane |
| (3) Cis 1,2 Dichloroethylene | (6) Methylene Chloride |

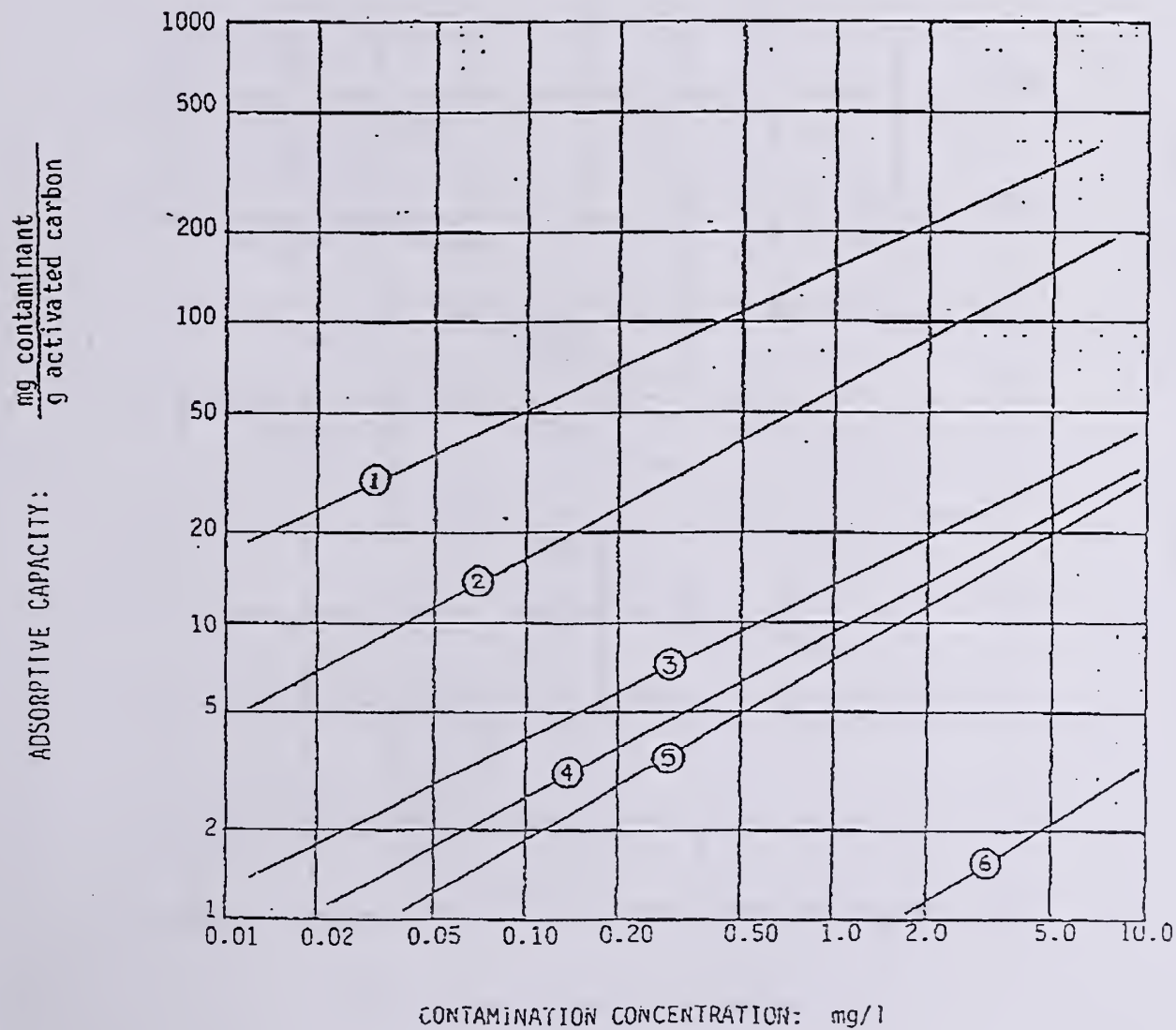


FIGURE 4
ACTIVATED CARBON ADSORPTION ISOTHERMS
AROMATIC SOLVENTS

- (1) m Xylene
- (2) Toluene
- (3) Benzene

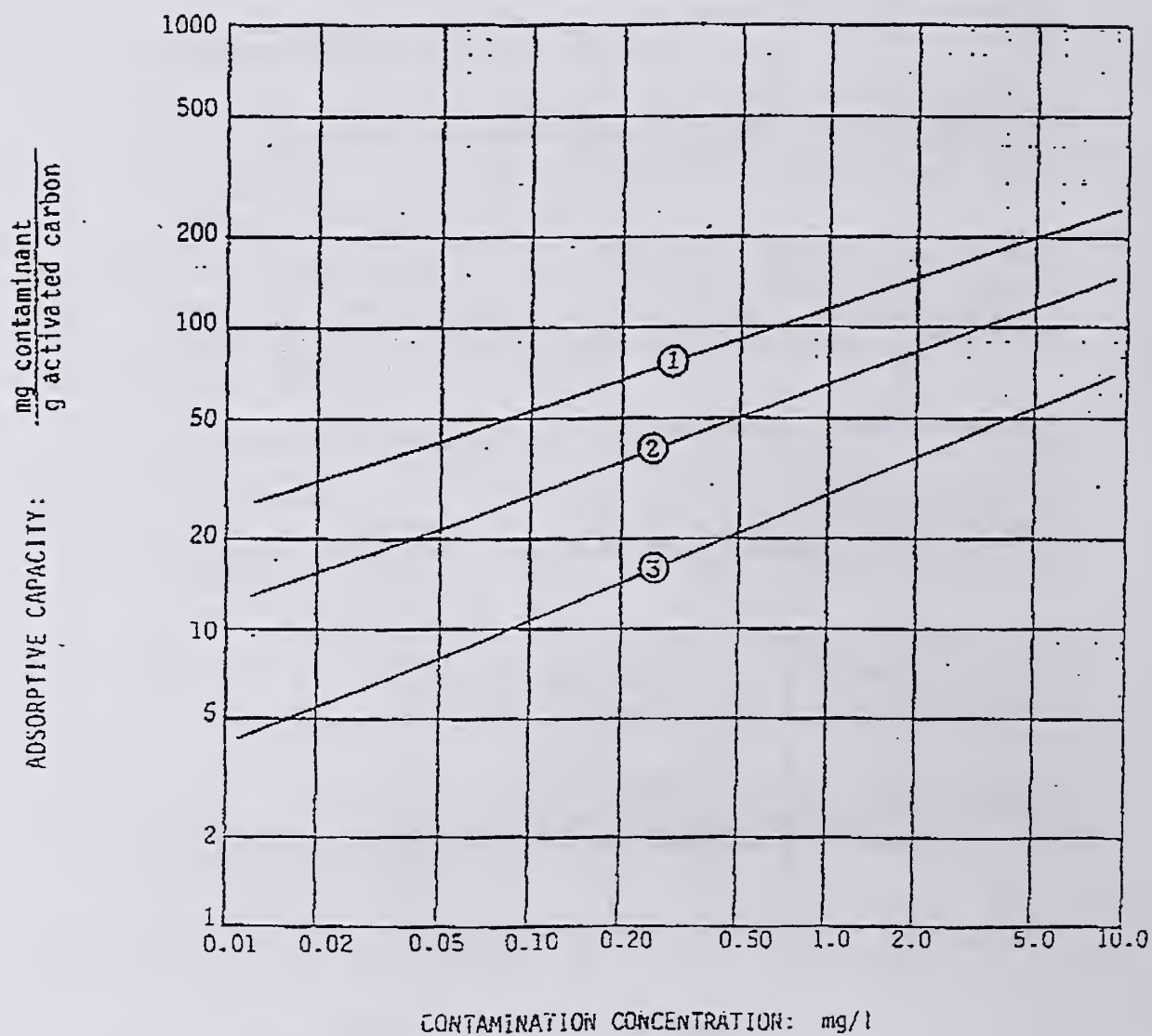


TABLE 1
Proposed VOC Regulations

VOC	Maximum Contaminant Level (MCL); ug/l
Vinyl Chloride	2
Benzene	5
Carbon Tetrachloride	5
1,2 - Dichloroethane	5
Trichloroethylene	5
1,1 - Dichloroethylene	7
p-Dichlorobenzene	75
1,1,1 - Trichloroethane	200

TABLE 2
ACCELERATED COLUMN TEST STUDIES
LOW LEVEL/SINGLE CONTAMINANT CASES

SITE:	MUNICIPAL GROUNDWATER	SYNTHETIC GROUNDWATER	SYNTHETIC GROUNDWATER	MUNICIPAL GROUNDWATER
CONTAMINANT	TRICHLOROETHYLENE	TRICHLOROETHYLENE	TRICHLOROETHANE	CHLOROFORM
CONCENTRATION, ppb	30	202	205	126
EFFLUENT OBJECTIVE, ppb	1	1	1	1
CONTACT TIME, minutes	10	8.5	8.5	12
GAC USAGE RATE, pounds, 1000 gals.	0.07	0.12	0.36	0.9
REALIZED CAPACITY mg/gm	3.6	14.1	4.8	1.2
ISOETHER (EQUILIBRIUM) CAPACITY, mg/gm	8.0	27.0	8.8	2.6
PERCENT OF EQUILIBRIUM CAPACITY REALIZED	45%	52%	54.5%	46%

TABLE 3
ACCELERATED COLUMN TEST STUDIES
SELECTED VOC CONTAMINATION CASES

SITE	CONTAMINANT	INDUSTRIAL GROUNDWATER ETHYLENE-	MUNICIPAL DRINKING WATER CHLOROFORM	GROUNDWATER	
				SINGLE COMPONENT 1,1,1 TRICHLORO- ETHANE	TWO COMPONENT CHLOROETHANE TRICHLORO- ETHYLENE
CONCENTRATION, ppb EFFLUENT OBJECTIVE, ppb CONTACT TIME, minutes GAC USAGE RATE pounds/1000 gallons REALIZED CAPACITY mg/gm ISOTHERM (EQUILIBRIUM)	CONCENTRATION, ppb	3300	135	55	165
	EFFLUENT OBJECTIVE, ppb	1	1	--	--
	CONTACT TIME, minutes	18	20	25	--
	GAC USAGE RATE pounds/1000 gallons	0.45	1.1	0.3	--
	REALIZED CAPACITY mg/gm ISOTHERM (EQUILIBRIUM)	61 90	1.0 2.7	1.2 3.5	-- 24.0
USAGE RATE FROM ISOTHERM CAPACITY pounds/1000 gals.		--	--	--	0.06
				0.13	(TOTAL = 0.19)
PERCENT OF EQUILIBRIUM CAPACITY REALIZED		67.8%	37.0%	63.3%	
				34.3%	
BACKGROUND CONTAMINATION		--	6 ppm TOC	165 ppb TCE	

TABLE 4

Adsorption System Capital Expenditure

BASIS: 600 gpm

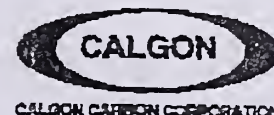
Adsorption equipment, installed	\$150,000
Foundation, installed	20,000
Well pump upgrade (if necessary)	10,000
Tie-ins; pump discharge/distribution	10,000
Equipment freight	10,000
Project management	25,000
Contingency	<u>25,000</u>
TOTAL PROJECT COST	\$250,000

TABLE 5

Adsorption System Annual Costs

Amortization of Capital (8.75% of 20 yrs.)	\$26,800
Maintenance (5% of installed capital)	\$12,500
Energy Costs (7 BEP for additional 15 psig; 8¢/KWH)	\$ 4,800
Carbon usage ¹ (40,000 lb. Calgon F-300 @ \$0.86/lb.)	\$34,400
Carbon Freight (two bulk trailer deliveries)	\$ 5,500
Total Annual Cost	\$83,500
Unit Cost	\$0.265/1000 gals.

¹ Assumes supplier of GAC can remove spent carbon and arrange for disposition of same in acceptable manner.

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INNOVATIONS IN TRADITIONAL TREATMENT

Removing EDB with GAC filters

Based on the most conservative estimates, computers predicted that the interval between carbon replacements could safely be extended to nine months for 50 percent of the filters.

**Roberto M. Narbaitz, Alan Baratta,
and Frances Z. Parsons**



Groundwaters are the drink-
ing water for 90 percent of Florida's resi-
dents. Contamination of groundwater is poten-
tially a serious public health problem. One of the
chemicals found in Florida's groundwaters is ethylene
dibromide (EDB), or 1,2-dibromoethane, which was
used primarily to control nematodes in citrus groves
in the central part of the state and in soybean and
peanut fields in the northern part of the state.¹
Groundwater contaminated with EDB has also been
reported in California, Hawaii, Georgia, Connecti-
cut, and New Jersey.²

The state of Florida
responded to the conta-
mination by creating a
State Interagency Task
Force on EDB to inform
the public, to survey all
potentially contaminated
wells, and to undertake
corrective action.³ Point-
of-entry (POE) treatment
systems at private homes
became an important
remedial action tool
because the contamina-
tion was found primarily
in rural areas. POE sys-
tems treat all of the water

Nearly 1,000 point-of-entry granular activated carbon (GAC) filters are efficiently removing ethylene dibromide (EDB) from contaminated groundwater throughout Florida. This article discusses the design, performance, and operational problems of the filters and assesses the possibility of extending the interval between GAC replacement from the current six months. Few breakthroughs have occurred in these filters, and most were caused by desorption during periods of sharp decreases in well water EDB concentrations. Because GAC loading data from the literature described the program data very well, they were used in conjunction with the equilibrium column model to predict the performance of the program's filters for different GAC replacement periods. Based on the most conservative estimate, maintenance for 50 percent of the filters could be extended to every nine months.

riologically acceptable, given that bacteria tend to proliferate within activated carbon filters.⁹⁻¹¹

A fixed maintenance interval is a basic criterion of Florida's program because it greatly simplifies management. First, there is no confusion over when every filter has to be maintained; this is important because there are nearly 1,000 filters in the program. Second, once the safety of a particular period is proven, monitoring of fumigant concentrations can be greatly reduced, leading to substantial savings. The cost of fumigant analysis for the one set of influent and effluent samples taken every six months is almost \$200 per location, whereas the cost of carbon and UV-lamp replacement is approximately \$500. Thus frequent monitoring, as conducted at a water treatment plant with GAC adsorbers, would be very expensive and hard to justify. Because the individual filters treat different well-water flow rates and different fumigant concentrations, different size filters are required to provide fumigant-free water for the same maintenance period. Monitoring represents a very large fraction of the cost of operating POE filter programs.¹²

The basic filter selection criteria were based on (1) the adsorption information developed by a consultant, (2) a six-month maintenance period, (3) the influent EDB concentration, and (4) the filter flow rate (Table 1). At wells with EDB concentrations of up to 10 µg/L, the POE systems should consist of one or two GAC filters providing an empty bed contact time (EBCT) of approximately 2.5 min. For larger concentrations, the systems selected provide an EBCT of approximately 5 min. Both these EBCT values are within the normal range for POE filters but below those used for water treatment plant GAC adsorbers.^{13,14} As shown in Table 1, the size and number of the filters were adjusted to treat the estimated water flow rate, while following the EBCT criteria.

The treatment systems were installed to serve (1) large community water systems; (2) private, semiprivate or institutional installations with large numbers of users, such as a trailer park or a school; (3) small businesses and industries; (4) systems supplying water to a few homes; and, (5) private homes. Eight hundred

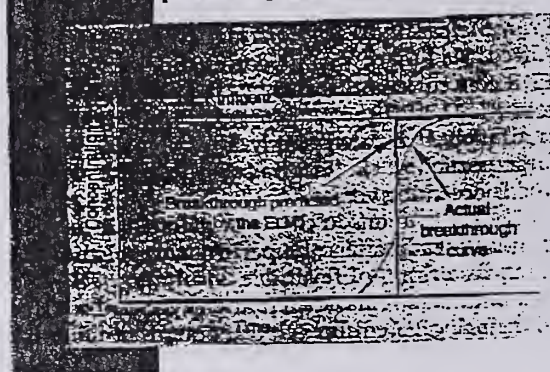
Ethylene dibromide, applied to Florida's citrus groves and soybean and peanut fields to protect the plants from nematodes, has found its way into the state's groundwater.

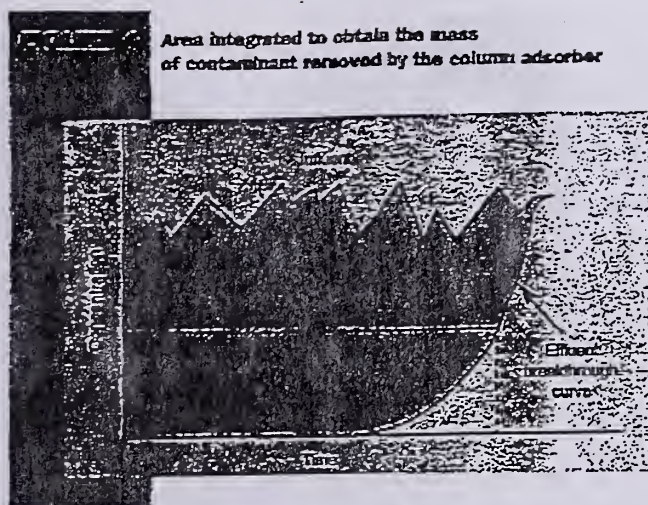


(or 83 percent) of the treatment systems are at private wells serving a single home. The next largest grouping, accounting for almost 13 percent of the filter systems, consists of systems supplying water to a few private homes. The nominal 2-cu-ft systems are the most common size used, accounting for 83 percent of the units at private well systems and 88 percent of the units within the entire program.

The remaining 114 larger filters within the program are of many different sizes and are connected either in parallel, in series, or both. Table 1 shows the most common filter sizes and configurations used within the program and their flow and concentration selection criteria. A few of the larger filter systems are not included in Table 1. All of the filters have short EBCTs. The majority, 82 out of 114 or 72 percent, of the larger-than-standard filters have a nominal size of 5 cu ft. They consist of two nominal 2-cu-ft GAC filters in series, each of which has a volume of 2.45 cu ft for a total of 4.9 cu ft—the nominal 5 cu ft. As indicated earlier, the nominal 2-cu-ft filters contain 2.2 cu ft of GAC, so the nominal 5-cu-ft filters contain 4.4 cu ft of GAC. Only 14 filter systems have carbon volumes of 10 cu ft (0.283 m³) or larger, which represents only 12 percent of the large filters and 1.5 percent of all of the filters in the program. Besides these systems, large GAC filters were installed at public water treatment systems in the cities of Lake Wales, Lake Alfred, and Harlem Heights.

Actual breakthrough and the breakthrough predicted by the equilibrium column





Area integrated to obtain the mass of contaminant removed by the column adsorber

Factors that affect performance of the GAC filters

The performance of POE activated carbon filters is affected by the same factors as water treatment plant adsorbers and, in addition, by some that are specific to POE units, such as short EBCTs and a tendency to desorb. The most important factors in the removal of toxic chemicals by activated carbon are the characteristics of the contaminant, the type of activated carbon, the presence of competing contaminants, the presence of naturally occurring background organic material (NOM), the water temperature, pH, and other water matrix characteristics. Competitive adsorption with NOM is particularly important as it can reduce the carbon's adsorption capacity by >50 percent.¹⁵⁻¹⁷ The performance of GAC adsorbers is also affected by the key adsorber design parameters: the EBCT and the hydraulic loading.

EBCT and hydraulic loading. POE filters in this program have EBCTs of only 2.7 min, which is much less than the 7.5- to 20-min EBCTs used in water treatment plants. From basic theory for single-contaminant adsorption, longer filter or column EBCTs result in more efficient use of the carbon's adsorption capacity. The longer columns resulting from longer EBCTs have a larger fraction of their GAC that reaches saturation and a smaller fraction of their GAC within the mass transfer zone that does not reach saturation. Thus, the average solid-phase concentrations achieved on the POE GAC filters will be smaller than those on water treatment adsorbers and even smaller than those predicted by bottle-point isotherms. Recent work by Hand et al.¹⁸ has shown that competitive adsorption with NOM can sometimes alter the increased loading with increased EBCT relationship discussed previously. This is primarily a func-

tion of the EBCT and the rates at which the synthetic organics adsorb. Flow program uses adsorbers with short EBCTs and EDB should be adsorbed much more rapidly than NOM. Thus, the adsorption of EDB is not expected to be significantly reduced by the complex competitive interactions with the NOM. And greater loadings may still be achieved by using longer EBCTs.¹⁸ The performance of the POE filters is also affected by some additional factors, such as the variability in well-water EDB and desorption.

Variability of well-water EDB and desorption. The well-water EDB concentrations are regularly monitored and in many wells there is great variability. Figure 2 shows the variability in EDB concentrations in a typical well. This may be attributed to, for example, the location of the contaminant plume, rainfall percolation, and soil desorption.

The POE systems treat water from existing wells. Generally there is no information on their location relative to the contaminant plume. Plume migration may be an important factor in future increases in EDB concentrations at some wells. To reduce the uncertainty over plume migration, it will be necessary to develop a network of monitoring wells and a monitoring program at each site. Given the large number of wells involved, such a task would be prohibitively costly. Using very conservatively designed POE systems is a method of reducing the risk.

Because the contaminated wells were mostly located in sparsely populated agricultural areas, the installation of POE treatment systems became the primary tool of remedial action.

It is reasonable to expect that EDB will leach from the soil in the unsaturated zone, resulting in high EDB groundwater concentrations after rainfalls. However, Melear and Parabeel¹⁹ observed that in I Alfred, Fla., there was no correlation between EDB concentrations and either the pumping rate or rainfall. The EDB was always present, but its concentrations fluctuated greatly. Thus, it is likely that a large portion of the EDB is adsorbed onto the soil and is desorbing very gradually.²⁰

These variations in the well-water EDB concentrations greatly affect the performance of the POE filters as a result of reversible adsorption. The limited information in the literature suggests that most of the halogenated aliphatic compounds tested so

adsorb reversibly.^{21,22} A consulting firm²³ conducted a desorption study by continuing its minicolumn runs using organic-free water as a column feed. During the first part of the experiment the column had been loaded with nanogram-per-litre levels of EDB, dibromochloropropane (DBCP), 1,2,3-trichloropropane, and 1,2-dichloropropane. The two columns were run for 600 bed volumes in the desorption mode, and during this time EDB was the only chemical to desorb. At both 300 and 600 bed volumes the desorbing EDB concentrations were approximately half that fed during the loading phase. Thus, EDB will desorb readily, and it is adsorbed more weakly than the other fumigants because they did not desorb.

A sharp reduction in the EDB concentrations entering a partially loaded filter could thus result in some desorption of previously adsorbed EDB. If there is more fresh carbon in the column, the contaminant will be adsorbed farther downstream in the column. If this additional adsorption capacity is not available, the contaminants will pass through the column and appear in the effluent. Because POE systems have short EBCTs, the latter is probably occurring in some filters. As shown in Figure 2, there will be fluctuations in the contaminant concentrations within the well water, so desorption is a strong possibility.

Other desorption problems may arise because of the on-off nature of the POE GAC filter systems. Leaching (desorption) of previously adsorbed contaminants may occur while the filter is not in operation, and these contaminants could be flushed out in the product water. This aspect requires further study and will possibly lead to development of guidelines for water usage like those for lead, i.e., running the water for a few minutes to rinse the system before taking a drink.

Therefore, the most important factors affecting the longevity of the GAC operating cycles are the EBCT and the variations in the EDB concentration. Contaminant desorption is an inherent problem of activated carbon adsorbers, and it can only be reduced by using larger adsorbers.

Modeling GAC filter performance

There are many methods of predicting GAC column performance (i.e., the breakthrough). They range from very simple models to very expensive and time-consuming pilot-scale tests to very elaborate mathematical models.^{24,25} Column performance modeling within this study will be limited to the equilibrium column model (ECM), the simplest method, because of several factors. First, there are too many filters (nearly 1,000) in the EDB filter pro-

Size and number of units in Florida's EDB program

Flow (gpm)	EDB Concentration (µg/L)	Filter Scheme	Nominal EBCT (min)	Nominal Size (cu ft)	Number of Filters
6	0.02-10	Single	2.7	2	803
10	0.02-10	Single	2.8	4	1
20	0.02-10	Parallel (2)	2.5	7	9
30	0.02-10	Parallel (2)	2.5	10	5
60	10.0-100	Series (2)	5.5	5	79
100	10.0-100	Series (2)	5.1	7	9
200	10.0-100	Series-parallel	5.1	14	1
300	10.0-100	Parallel (6)	5.1	20	1

gram to warrant elaborate analysis of each. Second, elaborate computer models require NOM measurements for their competitive adsorption calculations. As there are no NOM data available for these filter systems, the use of such models cannot be justified. Third, sophisticated modeling requires at least two effluent EDB concentrations during a breakthrough, and such data are not available for most systems.

In activated carbon adsorbers, mass transfer resistances slow the migration of the contaminant from the water phase to the interior surfaces of the GAC particles. These processes create the mass transfer zone within the column, and in this zone the carbon is only partially saturated, i.e., not in equilibrium with the feed. The ECM has the following characteristics. First, it assumes that adsorption is instantaneous, and, therefore, there is no mass transfer zone. Thus, instead of having an S-shaped breakthrough curve, this model assumes there is a breakthrough step (Figure 3) and the breakthrough time is independent of the breakthrough concentration. Second, it assumes that at the time of breakthrough all of the carbon is saturated; i.e., its solid-phase concentration is in equilibrium with the contaminant liquid-phase concentration in the feedwater. If the actual breakthrough curve is symmetrical in shape, then the ECM breakthrough time predictions should correspond to time when the actual effluent concentration reaches 50 percent of the value of the influent concentration (Figure 3).

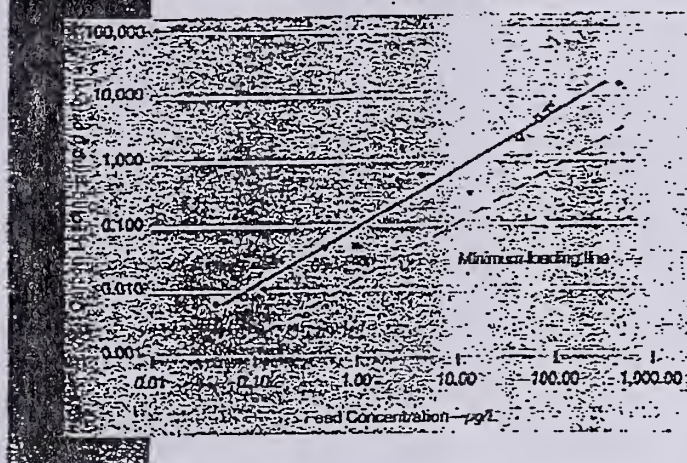
The equilibrium model mathematically predicts the breakthrough time by the following equation:

$$t_B = (V_B \cdot \rho_B) \cdot q_0 / (F \cdot C_0) \quad (1)$$

in which t_B is the breakthrough time (days); V_B is the volume of GAC in the column (m^3); ρ_B is the density of the GAC bed within the column (g/m^3); q_0 is the contaminant solid-phase concentration in equilibrium with the influent contaminant liquid-phase concentration (μg contaminant/ g GAC); F is water flow rate through the column (L/d); and C_0 is the influent contaminant liquid-phase concentration ($\mu g/L$). When the adsorption equilibrium is described by the Freundlich isotherm:

$$q_0 = k \cdot C_0^{1/n} \quad (2)$$

FIGURE 3 Data on EDB column loadings from the technical literature with the EDB minimum loading line



in which k is the Freundlich isotherm constant [$\mu\text{g/g GAC}/(\mu\text{g/L})^{1/n}$] and $1/n$ is the Freundlich isotherm exponent. The ECM can also be used with any other isotherm model including those used to describe multicomponent adsorption.

Although the ECM cannot predict the shape of breakthrough curves, it does provide a rough esti-

mate of service time.²⁶ It generally underestimates the breakthrough time because it neglects the mass transfer zone, should be used with caution.²⁶ Accordingly, it is common practice to divide ECM breakthrough time predictions by a factor of two when the ECM is used with bottle-point isotherms.

Another approach is to use the data with contaminant solid-phase concentration (loading) data from column adsorbers calculated at the breakthrough point. As discussed earlier, because of mass transfer resistances, the columns are not fully saturated, so their loadings are smaller than the equilibrium loadings predicted by isotherm experiments. This approach was chosen to analyze data from the EDB-fumigant filter program because it is particularly suitable for applications with similar conditions, i.e., filter size, flow rates, EBCTs, contaminants, water matrices.

The contaminant solid-phase concentration (loading) data from the column adsorbers must be calculated because it cannot be measured experimentally. The mass of contaminant removed from the water by the column is assumed to have

TABLE 2 Data on EDB column loadings from the literature

Breakthrough Curve Shape	Reference	Column Type	Carbon Type	PAC or GAC	EBCT, min	Hydraulic Loading, gal/ft ² /min	Water Type	Location	Feed Concentration, µg/L	Loading, µg/g	Other Contaminants, µg/L
Open circle	23	Mini-column	Calgon F-400	PAC	2.0	1.0	Spiked distilled	Lab	0.0077	0.0077	DBCH 0.0 TCP 0.0
Open circle	23	Mini-column	Calgon F-400	PAC	2.0	1.0	Spiked distilled	Lab	0.0077	0.0077	D-D 0.0
Open circle	23	Mini-column	Calgon F-400	PAC	2.0	1.0	Spiked distilled	Lab	0.0077	0.0077	DBCH 0.0 TCP 0.1 D-D 0.0
Open triangle	23	Mini-column	Calgon F-400	PAC (230-325)	0.04	0.04	Spiked distilled	Lab	967	5.197	
Filled triangle	23	Mini-column	Calgon F-300	PAC (230-325)	0.04	0.04	Spiked distilled	Lab	897	4.48	
Open square	4	Mini-column	Calgon F-300	PAC (230-325)	0.04	0.04	Spiked distilled	Lab	45	1.786	
Filled square	23	Photo-column	Calgon	GAC	8.7	1.0	Well water	Wales, Fla.	1.0	0.042	
Open inverted triangle	23	Photo-column	Calgon	GAC	10	6-10	Well water	Harlem, Heights, Fla.	0.5	0.04	
Filled inverted triangle	23	Photo-column	Calgon	GAC	3.0	1.0	Household	Fla.	14	0.248	
Open diamond	23	Lab	Calgon						4.7	0.509	
Filled diamond	23	Lab	Calgon						473.0	11.267	
Open triangle	28	Mini-column	Derco H-90	GAC			Well water	Nalcahu wells, Howell	0.1	0.0232	TCP 0.3

adsorbed. Mathematically, this can be expressed as

$$MCONT = \sum_{i=1}^N (C_{0i} - C_{outi}) \cdot F_i \cdot \Delta t_i \quad (3)$$

in which $MCONT$ is the mass of contaminant removed by the column (μg); C_{0i} is average influent contaminant liquid-phase concentration during period i ($\mu\text{g/L}$); C_{outi} is average effluent contaminant liquid-phase concentration during period i ($\mu\text{g/L}$); F_i is the average flow rate during period i (L/d); Δt_i is the duration of period i (days); and N is the total number of periods considered. Then,

$$q_{column} = MCONT / (V_B \cdot \rho_B) \quad (4)$$

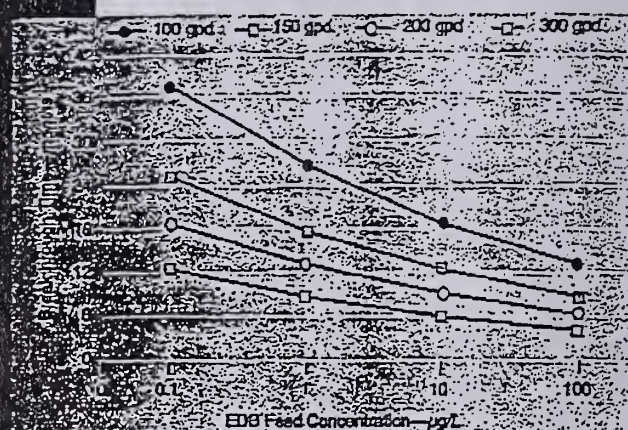
in which q_{column} is the average solid-phase concentration of the GAC within the column or filter (μg of contaminant/g of GAC); and $(V_B \cdot \rho_B)$ is the mass of GAC in the column. This mass of contaminant equals the average liquid flow rate multiplied by the area between the influent and the effluent concentration curves in a concentration versus time graph, shown as the shaded area in Figure 4.

The average column loadings (contaminant solid-phase concentrations) from the field are lower than those predicted by bottle-point isotherms, because they include mass transfer and competitive adsorption effects. As explained earlier, as the EBCT of a column increases, the adsorption capacity of the carbon is used more efficiently and approaches the capacity predicted by the bottle-point isotherms.

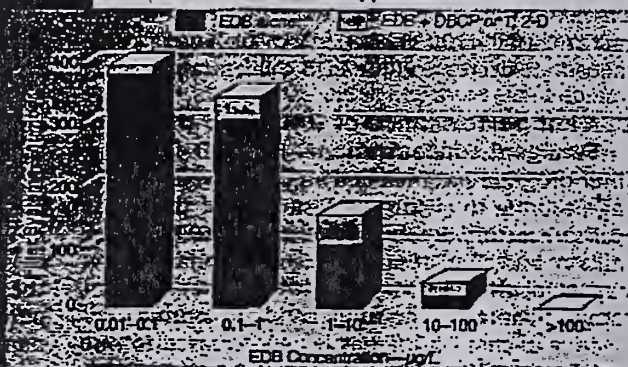
Survey and literature review of EDB adsorption data

The EDB adsorption data presented here were obtained through an extensive letter survey and literature review of POE systems and the adsorption of fumigants.²⁷ Most of the available EDB column loading data comes from minicolumns; however, there is some data from full-scale adsorbers (Table 2). The column data, shown in Figure 5, can be described very well by the solid straight line in spite of the differences in the activated carbon and the water being treated. To estimate the minimum performance that can be expected from a GAC filter, several steps were taken. First, because the data can be described by a straight line on a log-log graph, it was regressed using a Freundlich model. The best-fit line is shown as the solid line in Figure 5. Second, a line parallel to the best-fit line can be drawn through the point showing the greatest downward deviation from the best-fit line (not shown). Because these lines are parallel, the new line has the same Freundlich expo-

EDB breakthrough predictions for standard filters as a function of influent concentration and flow rate



Number of filters within selected ranges of average influent EDB concentration



nent as the best-fit line. Third, the coefficient of the lower line was then calculated. Fourth, an additional safety factor of two was applied to generate a minimum loading line for the evaluation of POE filter performance. The safety factor was intended to account for lower loadings that are achieved in the POE filters that have shorter EBCTs than conventional GAC filters. This literature-based minimum loading line, shown in Figure 5 as the dashed line, can be modeled by

$$q_{column} = 12 \cdot C_0^{0.85} \quad (5)$$

in which q_{column} is the loading in μg EDB/g GAC and C_0 is the column feed concentration in $\mu\text{g/L}$ EDB.

This loading curve was combined with the ECM by substituting Eq 5 for q_0 in Eq 1 to predict the breakthrough time of filters. Figure 6 presents the breakthrough time for the standard filters, which contain 2.2 cu ft of GAC, as a function of different water usages and EDB concentrations. This figure shows that the breakthrough time is very dependent on both these variables. For these POE systems to have

Analysis of EDB breakthroughs

Filter System	Number of Breakthroughs per Filter in System	Filters with This Number of Breakthroughs	Systems with This Number of Breakthroughs	Comments
2 single	1	1	1	Not breakthroughs
2 in series	1	1	1	Not breakthroughs
3 in series	1	1	1	Not breakthroughs
4 in series	1	1	1	Not breakthroughs
5 in series	1	1	1	Not breakthroughs
6 in series	1	1	1	Not breakthroughs
7 in series	1	1	1	Not breakthroughs
8 in series	1	1	1	Not breakthroughs
9 in series	1	1	1	Not breakthroughs
10 in series	1	1	1	Not breakthroughs
11 in series	1	1	1	Not breakthroughs
12 in series	1	1	1	Not breakthroughs
13 in series	1	1	1	Not breakthroughs
14 in series	1	1	1	Not breakthroughs
15 in series	1	1	1	Not breakthroughs
16 in series	1	1	1	Not breakthroughs
17 in series	1	1	1	Not breakthroughs
18 in series	1	1	1	Not breakthroughs
19 in series	1	1	1	Not breakthroughs
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22 in series	1	1	1	Not breakthroughs
23 in series	1	1	1	Not breakthroughs
24 in series	1	1	1	Not breakthroughs
25 in series	1	1	1	Not breakthroughs
26 in series	1	1	1	Not breakthroughs
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28 in series	1	1	1	Not breakthroughs
29 in series	1	1	1	Not breakthroughs
30 in series	1	1	1	Not breakthroughs
31 in series	1	1	1	Not breakthroughs
32 in series	1	1	1	Not breakthroughs
33 in series	1	1	1	Not breakthroughs
34 in series	1	1	1	Not breakthroughs
35 in series	1	1	1	Not breakthroughs
36 in series	1	1	1	Not breakthroughs
37 in series	1	1	1	Not breakthroughs
38 in series	1	1	1	Not breakthroughs
39 in series	1	1	1	Not breakthroughs
40 in series	1	1	1	Not breakthroughs
41 in series	1	1	1	Not breakthroughs
42 in series	1	1	1	Not breakthroughs
43 in series	1	1	1	Not breakthroughs
44 in series	1	1	1	Not breakthroughs
45 in series	1	1	1	Not breakthroughs
46 in series	1	1	1	Not breakthroughs
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86 in series	1	1	1	Not breakthroughs
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89 in series	1	1	1	Not breakthroughs
90 in series	1	1	1	Not breakthroughs
91 in series	1	1	1	Not breakthroughs
92 in series	1	1	1	Not breakthroughs
93 in series	1	1	1	Not breakthroughs
94 in series	1	1	1	Not breakthroughs
95 in series	1	1	1	Not breakthroughs
96 in series	1	1	1	Not breakthroughs
97 in series	1	1	1	Not breakthroughs
98 in series	1	1	1	Not breakthroughs
99 in series	1	1	1	Not breakthroughs
100 in series	1	1	1	Not breakthroughs
Total	100	100	100	Not breakthroughs

average influent EDB concentrations. Most of these filters treat low concentrations percent of the filters have average influent concentrations $<0.1 \mu\text{g/L}$ EDB; more than 78 percent have concentrations $<1 \mu\text{g/L}$ EDB; almost 96 percent have influent concentrations $<10 \mu\text{g/L}$ EDB. Only one system had average well-water concentration $>110 \mu\text{g/L}$ EDB. This given the low influent concentrations at many filters, likely that for these filters maintenance interval could be extended beyond the presently used six months. It should be noted that this assessment was based on average fumigant well-water concentrations.

a breakthrough time greater than one year, the flow rate must be $<100 \text{ gpd}$ (379 L/d) or have a commensurate decrease in the EDB concentration.

Current performance of GAC filter program

Fumigant concentrations. The EDB-fumigant filter program has included an extensive monitoring program to ensure performance of the filters was satisfactory. By the end of 1988, $>10,000$ filter influent and effluent samples had been analyzed. As expected, the vast majority of the filter effluent samples contained no fumigants. The normal frequency of monitoring has been decreased to one set of influent and effluent samples per six-month period. Wells with very high EDB concentrations are monitored on a more frequent basis. Ideally, sampling takes place just before changing the GAC, but because of the large number of filters involved, the sampling by state representatives and carbon changes by the commercial supplier frequently cannot be coordinated.

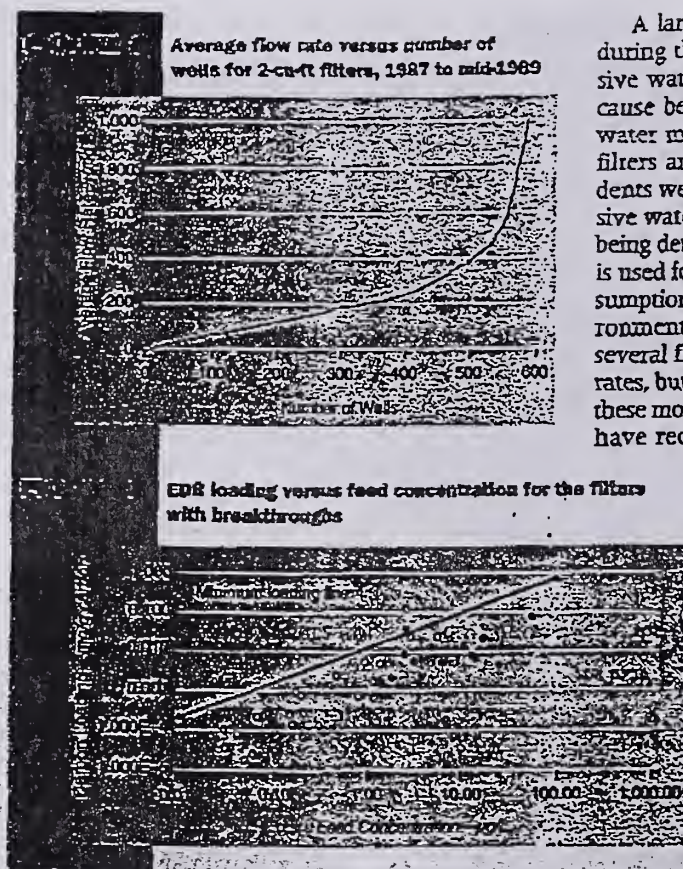
All of the wells within the program's database were included because their waters contained EDB. In 845 out of 962 (87.8 percent) water sources EDB was the sole fumigant identified. Thirty-three wells (3.4 percent) were also contaminated with DBCP, and 30 wells (3.1 percent) contained DBCP, EDB, and 1,2-dichloropropane (1,2-D). Fifty-three wells (5.5 percent) were contaminated with 1,2-D and EDB. *Trans*-1,3-dichloropropene was detected once; however, its presence was not confirmed by subsequent sampling. This fumigant, which is used as a substitute for EDB and DBCP, has a half-life of only three to 37 days depending on soil conditions.²⁹ Thus, this single detection is not surprising. In summary, EDB was present in all the wells, and in 12 percent of the wells it was accompanied by DBCP, 1,2-D, or both.

EDB concentrations. Figure 7 shows a bar chart of the number of filters within selected ranges of

concentrations. However, the well-water EDB concentrations are highly variable (Figure 2).

To address concerns of reduced adsorption capacity because of competitive adsorption from DB and 1,2-D, the wells were separated into two groups: those contaminated with EDB alone and those with EDB plus other fumigants. As shown in Figure 2, these other contaminants are more frequently found in wells with EDB concentrations $>0.1 \mu\text{g/L}$. The most wells with low EDB concentrations, which are the most likely to have their carbon replacement period extended, do not contain other contaminants. Thus, competitive adsorption among fumigants will not reduce the length of time the GAC remains effective within these filters. However, the well will still be some competitive adsorption between EDB and NOM.

The analysis of the EDB breakthroughs observed within the filter program gives an excellent indication of how well the filters are performing (Table 3). In four years, there have been >500 filter installations operating using six-month carbon replacement cycles. Thus the total number of filter cycles has been more than 4,000. In this period, there was a total of 89 filter breakthroughs at 53 different systems; these include many breakthroughs of the lead filter within systems of two filters in series, in which the product water quality was not compromised. Forty different systems experienced a total of 14 breakthroughs. A large number of these occurred during the initial stages of the program and were primarily caused by excessive water usage. Steps were taken to reduce the problem. The breakthroughs decreased, and only five installations have experienced more than one system breakthrough since the inception of the program. The low number of breakthroughs may be biased by the sampling information available. If a breakthrough is detected the GAC filters are replaced even before the six-



month service. In addition, the filters that have experienced breakthroughs are monitored more frequently. A further consideration is that the GAC systems provide complete removal of the contaminant for the majority of the time, whereas MCLs are levels of concern for continuous exposure during a lifetime.

In 117 filter systems containing DBCP or 1,2-D (or both) there were only five breakthroughs of these contaminants. Thus, the filter performance evaluation will be limited to the main contaminant, EDB.

Water-use rates. Water-use rates are extremely important because the breakthrough time is a function of the feed concentration and the quantity of water treated (Figure 6). Accordingly, the initial filter selection criteria were based on these two factors (Table 1). It should be noted that POE units are intended to treat the water used for indoor activities only. Individual indoor water usage rates may vary significantly, depending on the number and types of water appliances in use and on the number of people residing at the home. Average national indoor water usage rates are about 60 gpcd (227 Lpcd), with toilet flushing and bathing accounting for 70–80 percent of the water consumption.³⁰ Assuming the average home will have four residents, the typical POE system at such a home should treat an average of 240 gpd (908 L/d).

A large number of the breakthroughs occurred during the initial stages of the program, and excessive water use was suspected to be their principal cause because water use was not controlled. Total water meters were installed for all of the existing filters and for all those installed after 1986. Residents were also warned about the dangers of excessive water use. However, excessive water use is still being detected at some locations where filtered water is used for lawn watering and other high water consumption activities. The Florida Department of Environmental Regulation (FDER) experimented with several flow restriction devices to reduce water-use rates, but they caused excessive head losses. Because these modifications did not work very well and would have required the addition of booster secondary

pumps, they were not implemented.³¹ In addition, the most important factor is the total volume treated and not strictly the flow rate. Flow-restricting devices do not provide the total answer because they only reduce the gallons per minute treated, and the resident may still pass an excessive number of gallons through the filter by keeping the taps on longer. Some POU units, i.e., those small home filters used to treat water intended solely for drinking purposes, have automatic shut-off valves that are triggered after a given number of gallons are treated. Such an approach would be unrealistic because the home would be left without water for a few days until the state sup-

plier could change the GAC. Allowing residents to change the GAC when their systems shut off (because of excessive volumes treated) would be an inconvenience to some. For the state, which pays for the entire program, this policy would mean a loss of quality control because residents might disengage the shut-off controls or not maintain the systems properly. Development of a foolproof system is a challenge.

Meter readings are being routinely taken at each GAC change and are recorded in FDER's EDB-fumigant filter database. It should be noted that for some filters the meter readings within the database are missing or have questionable values. For example, usable flow information is only available for about 660 of the 801 standard filters. Average flow rates were calculated from the first and last meter readings within the period of interest, divided by the time between these two readings. The flow rates were arranged in ascending order, and they were plotted versus the number of filters with smaller flow rates, i.e., a cumulative average flow-rate graph. Figure 8 shows the cumulative average flow rate for the 2-cu-ft filters from 1987 to mid-1989. Many systems have very low water-use rates, possibly because they are at smaller households or vacation residences used for only part of the year. The changes in flow rates from one filter change to the next seems to show

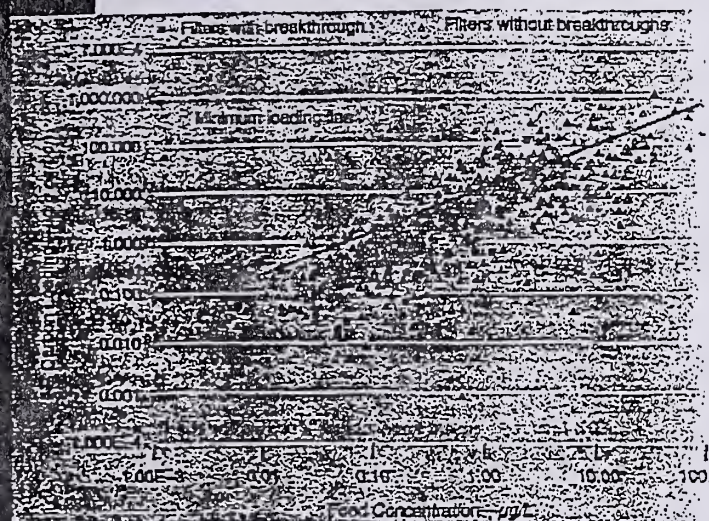
that only a small fraction of the filter systems are at seasonally inhabited homes. However, they may make up a larger fraction of those systems for which the flowmeter information is incomplete. Figure 8 shows that the flow rates increase very gradually up to filter 400 and then the flow rates increase exponentially. Approximately 400 (out of 662 or about 68 percent) of the 2-cu-ft filters had flow rates of 250 gpd (946 L/d) or less. Many filter systems had very high flow rates. Twenty wells had flows >800 gpd (3,028 L/d), of which five were flows >1,250 gpd (4,731 L/d). Because these flow rates are very high, to maintain the same-length service cycle for all the filters, it is necessary to install larger size filters at some of these locations. Water consumption rates did not change significantly with time.

A similar analysis of the 5-cu-ft filter systems shows that most have low flows. The frequency distribution pattern is very similar to that of the 2-cu-ft filters except that the highest flow rates are <500 gpd (1,900 L/d).

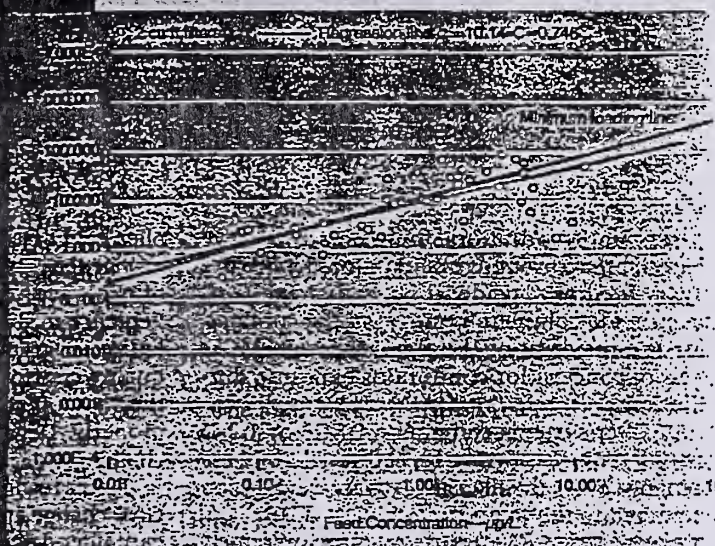
EDB loadings. Performance of the POE filters within the program will be evaluated using the ECM because of its simplicity and because there are so many filters within the program. The equilibrium approach was used in conjunction with the column loadings at breakthrough, because it considers, at least in part, the mass transfer resistances and competitive adsorption. Thus, the column loadings are necessary to predict the performance of the filters.

Only 89 EDB breakthroughs have been detected (Table 3). Because many of these breakthroughs occurred during the initial period during which the POE systems did not have flow meters, it is impossible to calculate the loadings for these events. Figure 9 presents the loadings calculated (using Eq 4) for the 36 breakthroughs that include flow data. These loadings were generally five to 50 times lower than those of the minimum loading line from the literature, and they showed greater variability than expected. Some spread in the data was expected because of differences in the

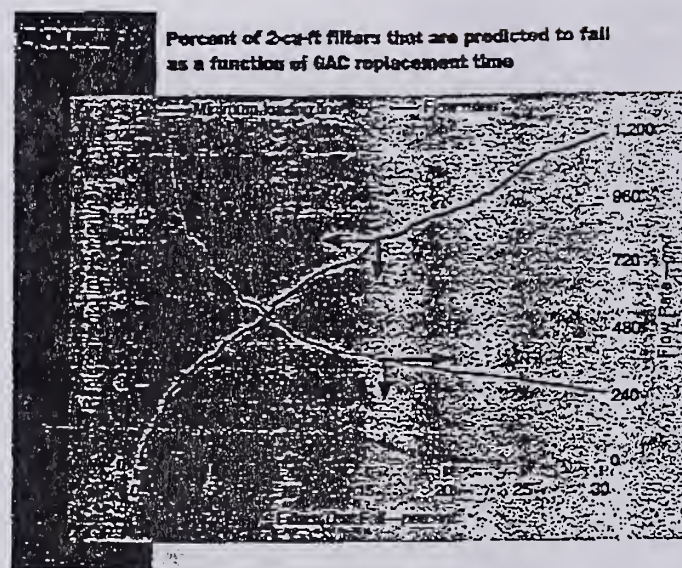
EDB loading versus feed concentration for all the 2-cu-ft filters



EDB loading versus feed concentration using the most reliable data set



water matrix; however, an investigation showed there were two more important reasons for the variability. First, many loadings were not accurate because they are based on only one or two data points. Second, there were large fluctuations in the well water concentrations. Only nine breakthroughs appeared to follow the textbook pattern; i.e., the influent concentrations remain consistent at a relatively high value and the effluent concentration is zero until breakthrough starts. The remaining filters showed questionable data or showed sharp drops in the well water EDB concentration, which probably caused previously adsorbed EDB to desorb, causing the breakthrough.



To make sure the loadings from the conventional breakthroughs were acceptable, the loadings of all the filters without breakthroughs were also calculated. Figure 10 presents these loadings along with those loadings from the textbook breakthroughs and those of the remaining breakthroughs. The non-breakthrough loadings were slightly higher than those with breakthroughs; this occurred because many breakthroughs were the result of desorption induced by a drop in the well-water EDB concentration.

The following constraints were applied to increase the accuracy of the loading data set. First, the loadings included were those from systems without breakthroughs. Second, only the loadings that were based on five or more data points were used. Third, the filters with nondetectable EDB levels in the well water were eliminated. As shown in Figure 11, this subset of loadings still shows some scatter, but their values are higher. Also, the literature-based minimum loading curve describes this selected data set very well. A regression of this data set shows that a slightly different loading curve would be obtained, but given that the literature minimum loading line was obtained independently, its predictions are excellent. It should be noted that because these filters had not reached breakthrough, their breakthrough loadings will probably be higher.

Expected effect of changing the interval between carbon replacements

The expected effect of changing the carbon replacement period was based on the predictions of the ECM model (Eq 1) coupled with the loadings described earlier. These predictions were conducted for all wells based on their individual average influent EDB concentration and average flow rate. The filter loadings, q_{column} from Eq 5, the minimum loading curve obtained from the literature review, were substituted for q_0 in Eq 1 to calculate the filter life.

The nominal 2- and 5-cu-ft filters were analyzed separately. There were only 720 wells with the 2-cu-ft size and 66 wells with the 5-cu-ft size with sufficient data to be included in the calculations. Figure 12 shows the percentage of the 2-cu-ft filters (out of 720) that fail as a function of carbon replacement time. The minimum loading line predicts that about 9 percent would fail using a six-month carbon replacement period. However, during the past four years, only 38 (or 4 percent) 2-cu-ft filters have shown EDB breakthroughs with such a carbon replacement period. This confirms that the minimum loading line is conservative.

If a nine-month carbon replacement period is implemented, it is expected that 18 percent (130 out of 720) of the wells will fail. A review of these predictions for possible patterns showed that

an excessive flow rates through the filters is the main reason for failure before nine months. Nearly 85 percent of the wells predicted to fail at nine months had flow rates of >350 gpd (1,325 L/d). Of the wells with average flow rates of <270 gpd (1,022 L/d), only four failed, and these had average EDB concentrations of 60 $\mu\text{g/L}$ or higher. Given these concentrations, 5-cu-ft filters should have been installed at these locations.

To continuously produce safe water at the locations with high flow rates, it is necessary to get the users to reduce their water consumption, to install larger filters, or to increase the frequency of the maintenance service. Because of the potentially high cost of the second option, the first and third options should be seriously pursued. It is important to investigate further and implement some form of corrective action at, at least, the five installations with more than one system breakthrough. As discussed earlier, the installation of flow-control devices does not necessarily reduce the total volume of water treated, which is the direct cause of the premature breakthroughs. However, such devices may reduce the problem and should be added, at least, to all the systems with excessive flow rate. Otherwise, the maintenance period of these filters should be shorter than six months.

These predictions are quite conservative because (1) the nonbreakthrough data are conservative and (2) the minimum loading curve, which describes the nonbreakthrough data well, predicted several-fold more breakthroughs than were observed in the field. A more conservative loading curve will minimize all possible breakthroughs that are due to inaccuracies in the minimum loading curve or desorption induced by concentration fluctuations. A more conservative loading equation was obtained by using the equation from the lower 95 percent confidence interval for the regression of the non-

breakthrough loadings (Figure 11). This loading is

$$q_{column} = 5.05 * C_0^{0.746} \quad (6)$$

This equation represents the addition of a safety factor of two to the minimum loading curve, already a conservative model. Thus, there should be a high degree of confidence in the safety of the predictions by this model. This new equation was used to reevaluate the filters within the program. Figure 13 shows that even with this more conservative criterion, 50 percent of the wells could operate safely with a nine-month carbon replacement period. As this implies that maintenance periods of different lengths would be required, a third and more frequent interval could easily be added for the systems with excessive flows.

The 5-cu-ft POE systems (i.e., two nominal 2-cu-ft filters in series) have not shown breakthrough over the past four years, whereas the literature-based loading curve predicted approximately 9 percent of the filters would fail with a six-month replacement interval. So again the minimum loading line is probably conservative, but the monitoring may have missed the breakthroughs. Calculations for the nine-month replacement period predicted only seven breakthroughs. These failing systems had flow rates of >420 gpd (1,590 L/d). Thus, for this size system, the flow rate is also critical.

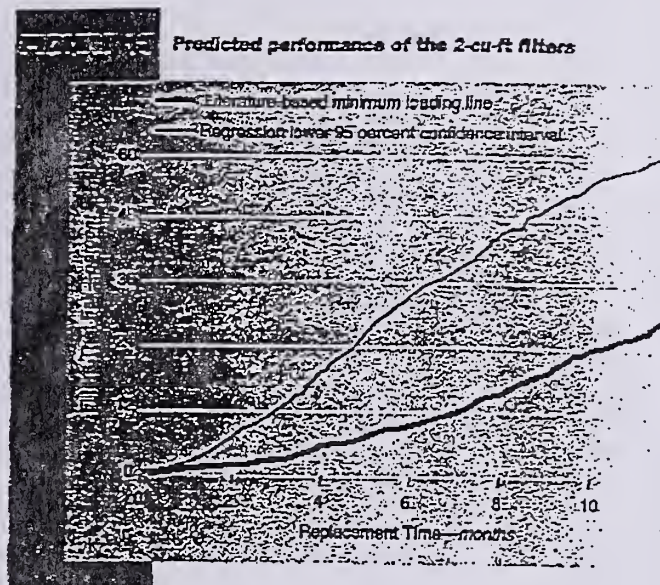
Conclusions

Florida's EDB-fumigant filter program consists of nearly 1,000 POE GAC filter systems installed to treat EDB-contaminated groundwater. Because of the relatively high cost of chemical analysis compared with the cost of carbon replacement, it is more practical to ensure safe water by designing very conservative systems and limiting monitoring. Florida's POE design criteria and six-month maintenance period have been very effective; there have only been a few recorded EDB breakthroughs. These premature breakthroughs can be attributed to excessive water use and to desorption induced by sharp variations in the well-water EDB concentrations.

All of the wells in Florida's program were contaminated with EDB, and 12 percent of the wells also contained DBCP or 1,2-D. More than 76 percent of the wells had average EDB concentrations <1 µg/L, and contamination with other fumigants occurred much more frequently in the wells with higher EDB concentrations. Thus competitive adsorption with other fumigants should not be a problem in the wells with lower concentrations of EDB, which are those most likely to have their carbon replacement period extended.

The EDB loadings from the literature were very consistent. Because of the well-water variability, de-

Predicted performance of the 2-cu-ft filters



sorption, and the limited data available, the load calculations for Florida's program had to be conducted very judiciously. Most of the more reliable field data were from filters that had not reached breakthrough; therefore, they underestimate the true loadings to certain extent. These loadings were surprisingly close to a literature-based minimum loading line.

Because these field loadings include the effect of mass transfer resistances for filters of this size and competitive adsorption effects, the equilibrium column model can be safely used to predict the performance of the filters within the program. Such an evaluation based on the minimum loading line in the literature is conservative because many more breakthroughs are predicted than have been observed in the field. These predictions showed that for 72 percent of the filters, the carbon replacement period could safely be extended to nine months. To greatly increase confidence that safe water is being provided, a more conservative loading curve was developed. It is based on the lower 95 percent confidence limit of the data and it predicted that 50 percent of the wells could safely undergo a change to a nine-month maintenance period. Most of the remaining systems should retain the six-month maintenance cycles. The predictions showed that excessive flows are the main reason that POE systems would fail under an extended carbon replacement period. Flow-restriction devices or more frequent GAC replacements are required for these filters.

Acknowledgment

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Removing EDB from Drinking Water

Cost and Performance of Carbon Filters

Michael D. Webb, P.E.

Florida Department of Environmental Regulation

Florida has come a long way toward rectifying the EDB problem since it was first discovered in the state's drinking water in 1983. A major contribution has been granular activated carbon adsorption.

Ethylene dibromide (EDB) had been used as an agricultural chemical more than 40 years when it was discovered in 1983 in ground water supplies in Hawaii. It had been thought to degrade rapidly when it entered the soil with no permanent detrimental effects to nearby ground water. After being notified of the discovery by Hawaii, Florida started an EDB testing program, since the chemical had been used in abundance for control of nematodes in citrus, peanuts, and other crops. Test results confirmed its presence in a number of wells.

An EDB task force, later changed formally to the Ground Water Protection Task Force, was formed from the Florida Department of Environmental Regulation (FDER) and the departments of Agricultural and Consumer Services, Transportation, Health and Rehabilitative Services, and Community Affairs. Its purpose was to perform further extensive testing and determine ways to correct the problem. State funding was provided only in areas where EDB had been applied by a state agency.

Testing of Wells

The testing program included all counties. Samples were collected mainly by the County Health Units and additional personnel hired by the FDER. Analytical work was performed by the Department of Health and Rehabilitative Services, the University of Florida, and Florida State University. Approximately 11,000 wells were tested, and about 1300 showed contamination ranging from the detection limit of 0.02 micrograms per liter (ug/l) to about 700 ug/l. Contaminated wells were found in 22 counties, with the most sites being in Polk, Highlands, Orange, Lake, and Jackson Counties. Most of the contaminated wells served private residences, but a number of small public installations, and several larger supplies, including Lake Wales, Lake Alfred, and Desoto City, were identified.

Solving the Problem

The short range solution to the EDB problem was to provide an interim source of uncontaminated water to the persons affected. Originally, bottled water was delivered and the home owner was informed of the availability of an alternate, uncontaminated source. If the home owner were handicapped or otherwise unable to obtain water from the alternate source, delivery of bottled water was continued.

The long range solution, obviously, was to remove EDB from the water supply, or to obtain another water source that met drinking water standards.

One approach was to construct new wells in the same general area but into a deeper aquifer. A private firm was contracted to construct 12 such wells in areas of contamination. Unfortunately, nine of the new wells tested positive for EDB. The conclusion was that this was not a reliable method.

At this point FDER and EPA contracted jointly with a private consulting firm to investigate the feasibility of removing EDB from water by air stripping and granular activated carbon adsorption (GAC). We knew work had been done in the past using these methods to remove a variety of organic chemicals from water, but we could find no data relating to the removal of EDB. Both methods were found to reduce EDB significantly—air stripping by 99 percent and GAC by 100 percent (*Evaluation of the Treatability of Ethylene Dibromide and Dibromochloropropane by Activated Carbon and Packed Column Air Stripping*, Environmental Science and Engineering, Inc., Gainesville, Florida). Because of the low maximum allowable concentration level of EDB set by state drinking water standards (0.02 ug/l), it was decided that GAC adsorption would be the more suitable method.

Small Whole-House GAC Filters

The state initially had to decide whether to provide filters only at the homeowners' drinking water taps ("point-of-use filter") or on the well pump discharge ("whole-house filter"). To provide the maximal degree of safety by eliminating EDB exposure from ingestion, inhalation, or dermal absorption, whole-house filters were chosen. They were installed on two private wells having concentrations of about 10 ug/l and 700 ug/l. EDB was removed to below the detection limit in both cases.

Whole house-filter design specifications were developed from data collected from the two test wells. Two final

designs were developed—for installations having up to 10 ug/l contamination, treatment consisted of a single, two cubic foot GAC unit, cartridge prefilter, and ultraviolet (UV) light source; for contaminations greater than 10 ug/l, a second GAC unit was added, and in some cases multiple units were necessary.

The final designs, installed on more than 500 private wells through December 1986, have been operating effectively in most cases (removal to below the detection limit of 0.02 ug/l). In isolated instances, excessive water usage (severe fixture leakage or commercial use) has caused premature breakthrough of the filters.

The carbon and UV units are normally replaced every six months, but many of the test cases were operated without breakthrough or other problems for nine months.

The cost of the whole-house filter is about \$1,200 for the single-GAC unit and \$1,850 for the dual unit. Annual costs are about \$620 and \$1080, respectively.

GAC Filters for Public Water Supplies

Nine EDB removal facilities were constructed for public water supplies. The facilities varied in flow rate from 70 gallons per minute (gpm) to 4.3 million gallons per day (mgd). Empty bed contact times ranged from about five to twelve minutes. Comprehensive operating data are not yet available, but

preliminary results indicate GAC filters effectively remove EDB from these supplies.

Larger installations are multiple, parallel tanks, while the smaller ones usually have two filter tanks in series and are piped such that the influent water can be changed from the exhausted filter to the partially used filter while the exhausted filter is being replaced. EDB sampling intervals range from monthly to once every three months. After more data are collected, the intervals may change.

So far, data adequate to calculate carbon usage rate have been collected from only one large and one small installation. The large filter was a 100 gpm, 67 cubic foot unit that operated 14 months before breakthrough. The small filter was a high usage rate, two cubic foot unit that operated about one month. The actual usage rates are compared to those calculated in the laboratory and in a pilot plant study in Table 1.

All of the filter units were installed in existing treatment facilities, and the required modifications and resulting cost varied widely. A typical example would be insufficient pumping capacity at the required discharge head, necessitating a new or reworked pump. Electrical wiring, instrumentation, and other components also may need to be reworked. Capital and engineering costs of several GAC installations are compared in Table 2.

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EDB from Page 11 Table 1. Carbon Usage Rates for Adsorption of EDB from Water.

	EDB Influent Concentration, ug/l	Carbon Usage Rate, pounds/1000 gallons
Laboratory Data	473	0.35
	96	0.154
	89.7	0.167
	45	0.21
	4.7	0.677
Pilot Plant Data	1	0.2
Actual Operation, Large Filter	0.5	0.104
Actual Operation, Small Filter	14	0.47

Table 2. GAC Costs

Size of Units	Approximate Cost \$	Cost per MGD Treatment
4 at 670 cu ft, 2.9 mgd capacity	590,000	203,000
6 at 760 cu ft, 4.3 mgd capacity	646,000	150,000
2 at 60 cu ft, 100 gpm capacity	20,000	139,000
2 at 30 cu ft, 90 gpm capacity*	15,000	118,000
2 at 74 cu ft, 220 gpm capacity*	35,000	110,000
2 at 24 cu ft, 70 gpm capacity*	16,000	159,000
2 at 27 cu ft, 80 gpm capacity*	16,000	139,000
2 at 32 cu ft, 75 gpm capacity	26,000	243,000

*Engineering costs not included.



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Writer's Direct Dial Number

October 27, 1983

Mr. Richard J. Miltner
Research Engineer
Drinking Water Research Division
USEPA
26 West St. Clair
Cincinnati, OH 45268

Dear Mr. Miltner:

I was pleased to talk with you last Friday about the work both USEPA and Calgon have been doing to evaluate the removal of trace concentrations of 1,2-dibromoethane (DBE) from water by activated carbon adsorption. It was gratifying to see how closely your isotherm data obtained with Calgon FS-400 carbon agrees with our isotherm data generated with FS-300 carbon.

Figure 1, attached, shows the adsorption isotherm we obtained using FS-300 carbon and DBE in deionized, distilled water. I have taken the liberty of including your FS-400 adsorption data for comparison. Table I shows minimum expected carbon uses for complete removal of DBE from water in a well designed column adsorber using the isotherm line in Figure 1. Table II shows the results of an Accelerated Column Test we performed to demonstrate that carbon column adsorption can achieve effluent DBE concentrations below 0.02 µg/l (20 ppt). The low level DBE analyses were performed using a modification of the California State Department of Health Services Method for the analysis of 1,2-dibromo-3-chloropropane (DBCP) in water. This liquid-liquid extraction method was chosen based upon our experience with DBCP in California and discussions I had with USEPA analytical specialist Bob Turner.*

Calgon looks forward to continued cooperation with USEPA in solving the difficult problems of protecting and restoring the quality of our nation's groundwater. We are eager to receive a copy of your new paper on carbon adsorption isotherms of volatile organic compounds at low concentrations. Calgon has much valuable dynamic column adsorption data for these same volatile compounds in groundwater that may be of interest to USEPA.

Sincerely,

CALGON CORPORATION

Danny L. Mercer
Research Chemist

DLM/job
Attachments

cc: R. P. O'Brien
R. Turner

→ R. Thomas *

bcc: R. V. Carrubba
J. H. Mahon
P. A. Reiser
J. D. Sember

MEMO



TO Distribution
FROM D. L. Mercer
SUBJECT 1,2-DIBROMOETHANE (ETHYLENEDIBROMIDE)

DATE 10/13/83

INTRODUCTION

In response to the concern over low level contamination (20-100 ppb) of groundwater by the compound 1,2-dibromoethane (DBE), Carbon R&D performed carbon adsorption tests to determine: 1) the adsorption capacity of FS-300 Carbon for DBE, and 2) to demonstrate the feasibility of using FS-300 Carbon in a column adsorption system to reduce the concentration of DBE to less than 0.1 ppb ($\mu\text{g/l}$).

SUMMARY AND CONCLUSIONS

A 0.557 mg/l synthetic solution of DBE was reacted with various doses of FS-300 activated carbon in zero-headspace reaction flasks to generate the isotherm shown by Figure 1. A 0.06 mg/l (60 ppb) synthetic solution of DBE was tested by the Accelerated Column Test to demonstrate the feasibility of using FS-300 activated carbon to reduce the DBE concentration to less than 0.1 ppb ($\mu\text{g/l}$). From these tests, the following conclusions can be drawn:

1. Using the isotherm data from Figure 1, Table I presents theoretical FS-300 Carbon usage data for complete removal of DBE from a synthetic solution. The data show that in the absence of competitive adsorption, the FS-300 Carbon use rates for removal of DBE in a properly designed column adsorption system are less than 0.2 lb/1,000 gallons of water treated for influent DBE concentrations less than 0.3 mg/l (300 ppb).
2. Table II presents results from an Accelerated Column Test simulating the treatment of a 60 ppb synthetic DBE solution in a standard 10 ft ϕ adsorber containing 20,000 lbs of FS-300 Carbon operated at a surface loading rate of 3 gpm/sq ft and an empty bed contact time of 23 minutes. The data show that the DBE concentration can be effectively reduced to less than 0.1 ppb.

D. L. Mercer - 8565

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Attachments

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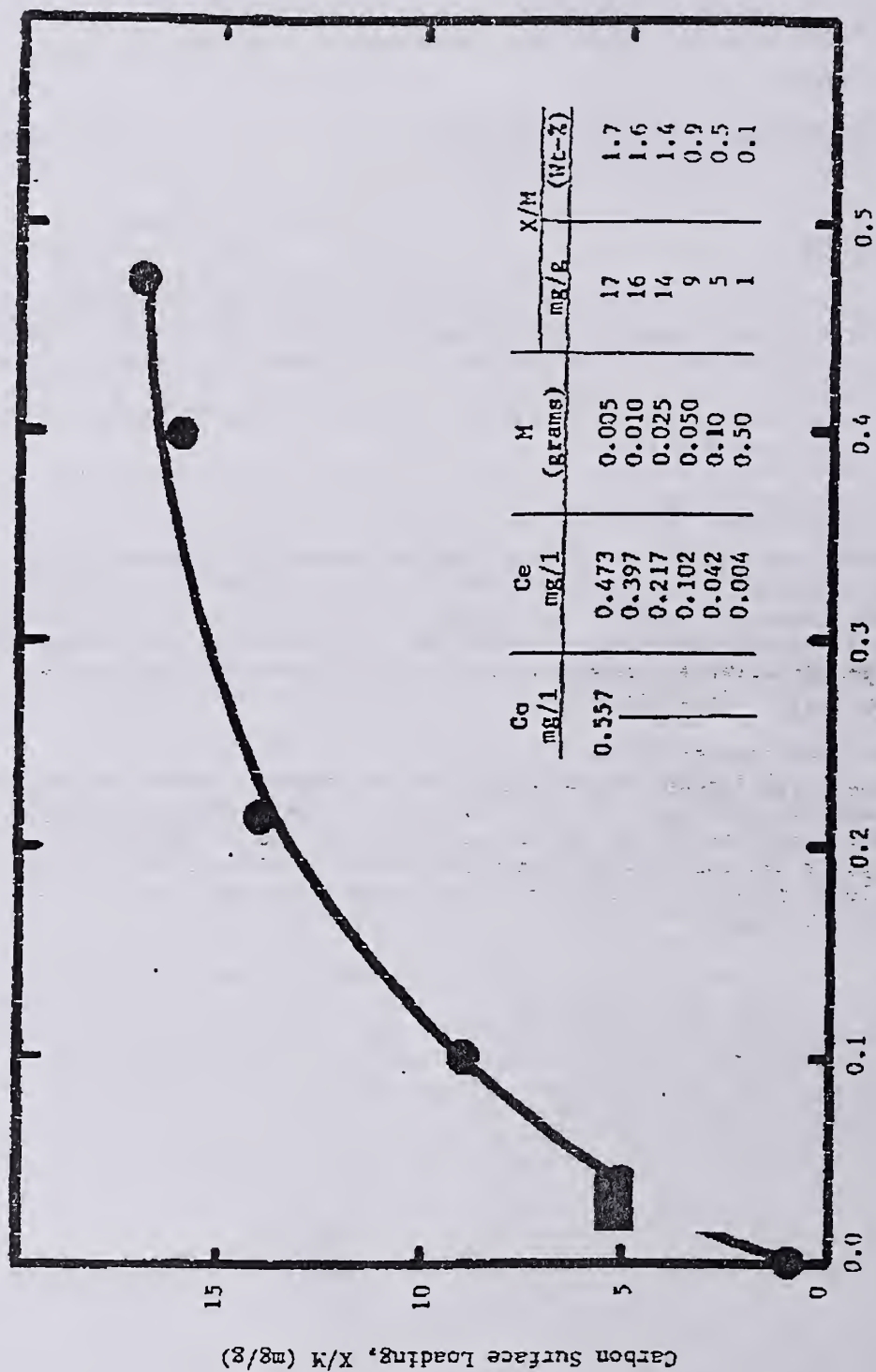


FIGURE 1. ADSORPTION OF 1,2-DIBROMOETHANE BY CALGON FS-300 ACTIVATED CARBON

TABLE IMINIMUM THEORETICAL CARBON USAGE FOR COMPLETE
REMOVAL OF 1,2-DIBROMOETHANE BY FS-300 CARBON

<u>C₀</u> <u>(mg/l)</u>	<u>X/M</u> <u>(mg/g)</u>	<u>Minimum Theoretical</u> <u>Carbon Use</u>	
		<u>(g/l)</u>	<u>(lb/1,000 Gal)</u>
0.300	15	0.020	0.17
0.200	13	0.015	0.13
0.100	9	0.011	0.09
0.050	5	0.010	0.08
0.020	3	0.007	0.06

DLM/job
10/13/83

TABLE IIACCELERATED COLUMN TEST SIMULATION OF 1,2-DIBROMOETHANE
REMOVAL FROM A SYNTHETIC SOLUTION BY A COLUMN ADSORBER
OF FS-300 ACTIVATED CARBONTest Conditions Simulated

Flow Rate - 240 gpm
Adsorber Dimensions - 10 ft Ø x 10 ft high
Surface Loading Rate - 3 gpm/sq ft
Carbon Weight - 20,000 lbs
Empty Bed Contact Time - 23 minutes

<u>Sample</u>	<u>DRE Conc. (µg/l)</u>
Feed #1	61
Feed #2	60
Composite Effluent #1	<0.02
Composite Effluent #2	<0.02

DLM/job
10/13/83

Water Treatment

Activated Carbon Treatment Restores Acton Water Supply

District lost one million gallons of water per day, 40 percent of its water supply, when two wells were found chemically contaminated.

By John E. MacLeod and George R. Allan

Many New England municipalities have traditionally taken pride in the fact that water from their gravel-packed wells requires no treatment. Some do not even require chlorination. Unfortunately, the purity of these supplies has led some communities to place too much faith in nature's ability to protect the quality of their groundwater.

During the past four years, the closing of more than two dozen public water supplies in Massachusetts has demonstrated the susceptibility of groundwater to contamination. One of the first communities to be affected was Acton, a town 22 miles west of Boston.

Acton's water district lost one million gallons per day (mgd), 40 percent of its water supply, in December 1978 when two wells were taken out of service after several organic chemicals — including trichloroethylene, dichloroethylene, methylene chloride, and benzene — were detected. The district removed the wells from service until the source and toxicity of the contaminants could be resolved.

The two wells — Assabet No. 1 and Assabet No. 2 — are in the Sinking Pond aquifer, which encompasses approximately 375 acres. Sixty-five of the acres are owned by the water district. More than 100 test wells penetrated the aquifer's sand and gravel overburden during various investigations, making it one of the most studied aquifers in Massachusetts.

The municipal wells each have a yield of 0.5 mgd. During 1978, their average total monthly withdrawal was 17 million gallons. In addition to these two wells, the aquifer is the site of three industrial wells, pumping an average of 11 million gallons per month. This water is used for industrial cooling, and is then recycled back into the aquifer.

A year-long hydrogeological study conducted of the Sinking Pond aquifer

in 1979 determined the probable cause of contamination to be the waste disposal practices of a nearby chemical plant. The primary sources were a landfill and several lagoons filled with liquid wastes, located approximately 2,500-3,000 feet north of the municipal wells. The groundwater gradient across the aquifer slopes from north to south.

The study also delineated an extensive plume of contamination extending to within 1,000 feet of Assabet No. 2, the well closest to the chemical plant. Concentrations of total chlorinated hydrocarbons in this contaminated plume were as high as 10,000 parts per billion.

With the need for immediate action to meet the water needs of its customers, the district took the following approach to the problem:

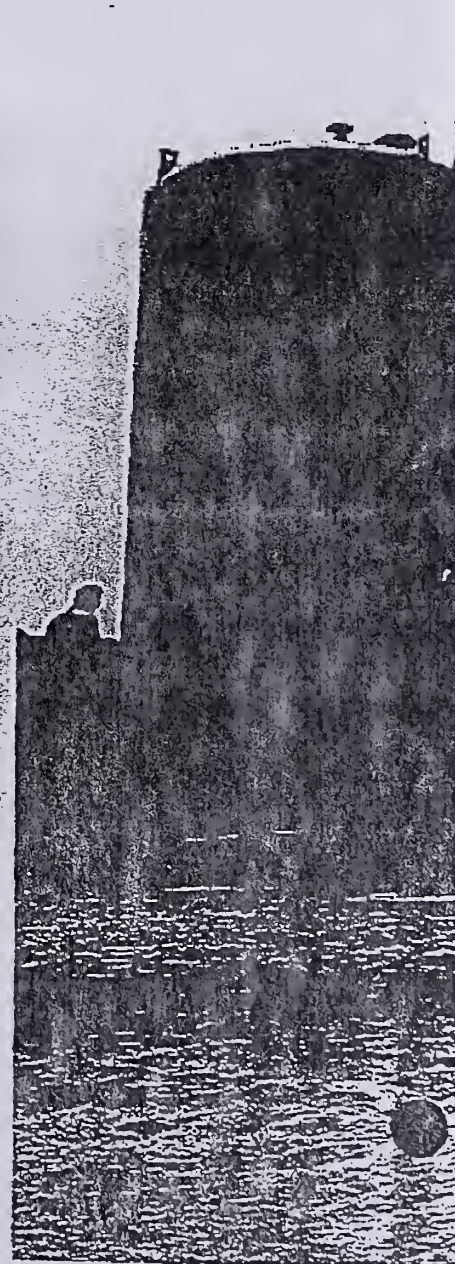
- banned the use of outside water, prohibiting such activities as lawn watering and car washing;
- initiated public education programs promoting water conservation;
- installed a booster pumping station to draw water from the neighboring town of Concord; and
- initiated a maintenance program to improve the efficiency of the remaining active wells.

The success of these short-term programs enabled the water commissioners to concentrate on two long-term goals: obtaining additional permanent water supplies, and restoring the Assabet wells to usable conditions.

The first step toward achieving the goals was increasing funding for water supply investigations from the previous \$15,000 annual appropriation to a range of \$75,000 to \$100,000 per year.

Investigators located three sites producing satisfactory test results. The sites

Acton used two granular activated carbon treatment tanks to help restore its wellwater quality.



have an estimated combined safe yield of 1.0 mgd. The wells are in North Acton, about two miles from the existing distribution system. The district is proceeding with the acquisition of approximately 65 acres at the three sites.

The board of water commissioners also took other actions to ensure an adequate water supply. The board obtained voter approval to fund a town-wide hydrogeological study to assist in the management and protection of current and future water source supplies. A five-member land-water management advisory committee was appointed to

assist the board in studying the problems facing the district.

The district then began investigating possible treatments for the Assabet wells. The first step was building a pilot plant that treated water from Assabet No. 2, the well with the higher level of contaminants. The plant used granular activated carbon (GAC) with and without aeration to treat the water. The investigation, which continued through the second half of 1979, indicated the GAC and aeration were effective in removing the chlorinated hydrocarbons from the aquifer.

During 1980, the water commissioners' attention focused on the legal aspects of the contamination. In April, the federal Environmental Protection Agency filed suit against the chemical company, demanding it "remove, neutralize, or isolate all chemical wastes and contaminated soil" on its property. This was the first suit filed in Massachusetts under the federal Resource Conservation and Recovery Act.

Six months later, the suit was settled out of court by a consent decree under which the company agreed to develop a plan to clean up the aquifer and restore it to usable conditions. The water district was not a party in the EPA suit.

However, in October 1980, the commissioners filed a \$3 million suit against the chemical company based on the loss of the two public water sources and the contamination of the aquifer. The suit is pending in federal court.

During the summer of 1981, the district stepped up efforts to treat the Assabet wells. Representatives of the Calgon Corp., of Pittsburgh, Pennsylvania, explained the use of granular activated carbon for removing organic contaminants from groundwater.

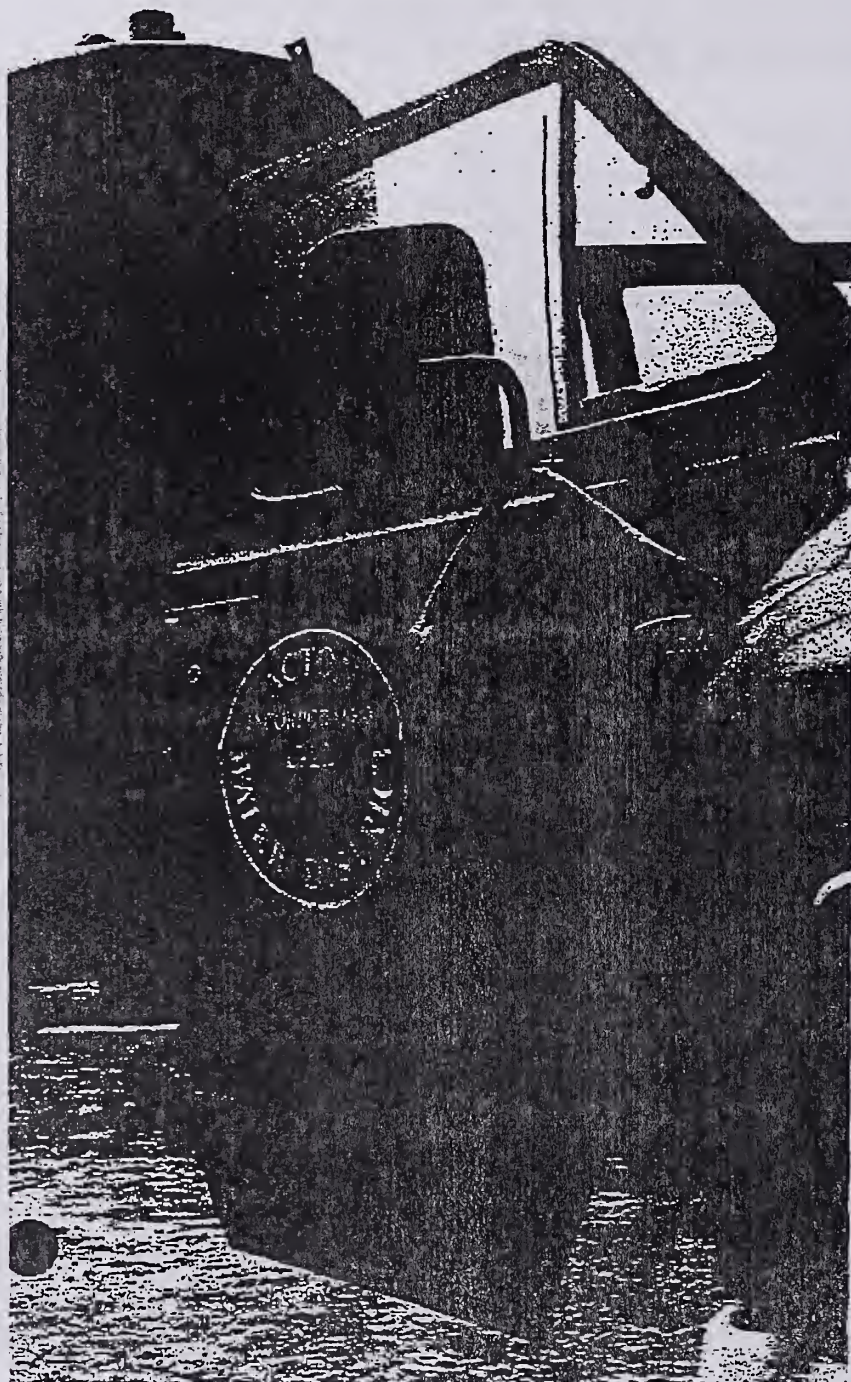
Calgon Corp. conducted an accelerated column test in the fall of 1981, showing that carbon treatment would remove volatile organics to less than detectable levels—less than one part per billion. Calgon proposed a full-scale, pilot-plant trial to determine carbon exhaustion rates under actual field conditions. The study permitted the evaluation of the adsorption rates of volatile organics under varying concentrations, while providing the district with 0.5 mgd of water.

The district's March 1982 annual meeting appropriated \$200,000 to fund the full-scale pilot plant. The chemical company offered to contribute \$100,000 of the expense, which the district accepted.

The full-scale pilot plant was designed to treat the 0.5 mgd from Assabet No. 1. Calgon was the successful bidder to furnish two adsorbers and 40,000 pounds of GAC. Water district personnel installed the adsorbers and interconnecting piping in a manner allowing the treatment of the Assabet wells.

The two adsorbers were piped in series. This permitted evaluation of the GAC exhaustion rate in the first adsorber, while the second continued to polish the effluent.

The district established a criterion for the treated water: a maximum total volatile organics content of 5.0 parts per billion. To monitor the quality, an extensive sampling and testing program was adopted. Not only was this carried out by the Massachusetts Department of



Water Treatment

The Cost of Acton's GAC Treatment

Installation cost

Foundation and site work	\$ 5,500
Piping	
(material only; labor by district employees)	20,000
Crane rental	1,100
Calgon set-up	
(including activated carbon)	60,400
Miscellaneous	
(chemical feeder, alarms, fence, etc.)	6,400

Total \$93,400

Monthly operating cost

Calgon rental	\$ 4,945
Electricity for well pump	1,800
Sampling and testing	2,000

Total \$ 8,745

Environmental Quality Engineering and the federal EPA, but three private firms also were employed for the task. At least two labs performed analyses on samples taken weekly from the influent, the effluent from each of the adsorbers, and samples from several outlying monitoring wells.

Construction started in May 1982 and, by June, water from Assabet No. 1 was pumped through the adsorbers. During the first two weeks the system was in operation, the effluent was discharged into the Sinking Pond aquifer. After laboratory testing confirmed the treated water's purity, approval was granted in July 1982 to put Assabet No. 1 back into the municipal system—after its 3½-year absence. Now, the water is fluoridated prior to GAC treatment and, after treatment, is chlorinated to a 0.25 mg/L residual.

Early tests showed the raw water pumped from the well did not contain any detectable level of volatile organic

contaminants. This was expected, because the normal groundwater flow pattern in the aquifer under non-pumping conditions would carry the plume of contamination past this well. Pumping, however, was expected to eventually draw contaminated water into the well. A second reason for the lack of measurable contamination was the intercepting effect of the pumping of Assabet No. 2, which was being piped to Sinking Pond by the chemical company as part of its pumping test of the aquifer.

After one month of pumping, the first chlorinated hydrocarbons were detected in the raw water. The two primary contaminants were 1,1,1 trichloroethane and 1,1 dichloroethylene. Contaminant concentrations continued to increase for the testing duration, reaching a level in excess of 150 parts per billion.

Contamination levels exceeding the

water district's standard of 5.0 parts per billion for total volatile organics were not measured in the effluent from the first adsorber until after 27 weeks of continuous use. During this period, the GAC in the adsorber had treated a total of 88 million gallons of water.

The average influent concentrations of trichloroethane and dichloroethylene were 40 parts per billion and 1.5 parts per billion, respectively. Under these conditions, carbon usage at the pilot plant was 0.34 pounds per 1,000 gallons of treated water.

Final treatment costs cannot be established until the raw water quality stabilizes. Factors affecting the cost of treating water with GAC include the types and concentrations of contaminants in the influent, the flow rate, and the effluent criteria.

This pilot plant demonstrated GAC could effectively remove contaminants in the concentrations found in the Sinking Pond aquifer.

Yet, raw water contamination levels continued to increase. The district evaluated air stripping in packed towers as a pretreatment to extend the life of the GAC. In early 1983, the district voted to make a carbon installation permanent, and to develop and install an aeration system. In addition, the district appropriated \$11,000 to purchase a portable gas chromatograph. This instrument will augment the present sampling program and monitor water quality at other wells.

Acton's approach to combat contamination and manage groundwater resources is a model for communities facing similar problems. Until now, financial considerations usually prompted municipalities to seek alternative water sources instead of treating contaminated existing supplies. Acton's experience has demonstrated that treating water contaminated by volatile organics is an economical and viable procedure. □

John E. MacLeod is district manager of the Acton Water District. George R. Allan is vice president of the consulting firm of Dufresne Henry, Inc.

**THE LABORATORY
EVALUATION OF GRANULAR
ACTIVATED CARBONS
FOR LIQUID
PHASE APPLICATIONS**



PITTSBURGH ACTIVATED CARBON
DIVISION OF CALGON CORPORATION
SUBSIDIARY OF MERCK & CO., INC.

CALGON CENTER, BOX 1346, PITTSBURGH, PA. 15230

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INTRODUCTION

Granular vapor phase activated carbons for the removal of gaseous contaminants and condensible vapors from gas streams have been employed for many years. Considerable data can be found in literature on the adsorption of specific gases and vapors; and proven methods exist for the design of columns for continuous gas purification and solvent recovery.

Granular, regenerable activated carbons, for the removal of soluble colorants and contaminants from liquids, are of recent origin. Most of the published data in the field of liquid phase activated carbon adsorption are applicable only to pulverized carbon in batch systems. A sound method for predicting the general performance of granular carbon in columns from batch data is not available at this time. Consequently, until valid mathematical data can be established, each new application for granular carbon must be considered individually. This discussion is primarily concerned with descriptions of the laboratory procedures that we have found most valuable for obtaining preliminary column design data for use of granular activated carbon in liquid phase applications.

Whether granular activated carbon is being considered for a new application or for the replacement of a pulverized carbon system, it is essential to determine its efficiency and the related advantages for the specific application. A complete laboratory investigation, in general, would consist of two parts. First, preliminary tests would be performed to demonstrate the feasibility of granular carbon treatment. Secondly, laboratory column tests would be made to obtain operating capacities as well as plant column design data.

Depending on the amount of background knowledge available, the preliminary tests will in some cases be unnecessary. Let us assume, however, for the sake of discussion, that we are dealing with an application about which little is known, and consider first the preliminary investigation.

ADSORPTION ISOTHERMS

Theory

A relatively simple method of investigation is available concerning the feasibility of column treatment with granular activated carbon for a particular application—that is by inspection of the decolorization or adsorption isotherm. A liquid phase isotherm shows the distribution of adsorbate between the adsorbed and the solution phases and is a plot of the amount of impurity adsorbed against the amount of impurity remaining in solution. In the case of liquid phase applications, we can generally obtain straight line plots by making use of the empirical Freundlich equation which relates the amount of impurity in the solution phase to that in the adsorbed phase by the expression:

$$x/m = kc^{1/n}$$

where x = amount of color adsorbed

m = weight of carbon

x/m = concentration in the adsorbed state (i.e., the amount of color adsorbed per unit weight of carbon)

c = equilibrium concentration in solution after adsorption

k and n are constants.

Taking logs of both sides:

$$\log x/m = \log k + 1/n \log c$$

which is the equation of a straight line whose slope is $1/n$ and whose intercept is k at $c = 1$. Therefore, if x/m is plotted against c on log-log paper, a straight line should be obtained. This is true for most of the systems encountered, primarily because we are normally concerned with the removal of low concentrations of contaminants or colorants and the Freundlich equation holds quite well for dilute solutions.

Experimental

Data for plotting isotherms are obtained by treating fixed volumes of the liquid to be tested with a series of known weights of carbon. The carbon-liquid mixture is agitated for a fixed time at constant temperature. After the carbon has been removed by filtration, the residual color of the solution is determined. If the impurity is colorless, the residual concentration may be measured by an alternative analytical method. From these measurements, all of the values necessary to plot an isotherm may be calculated.

SELECTION OF EXPERIMENTAL CONDITIONS

Temperature

If the solution to be treated has a viscosity in the vicinity of six centipoises or less, the isotherm tests may be performed at room temperature. However, if the liquor is more viscous, such as a sugar syrup, or is solid at room temperature, such as a wax, it is necessary to increase the temperature to obtain a liquid sufficiently fluid to ensure good contact with the carbon. A good rule to follow is to employ temperatures no higher than necessary to obtain the desired viscosity characteristics. In many cases, temperature limits will be imposed by the thermal stability of the material being tested or by existing plant practice.

Contact Time

A minimum of one hour is recommended. It is advisable to perform a preliminary experiment in which fixed volumes of the test liquor are contacted with a fixed weight of carbon for one, two, three and four hour periods. If per cent color removal is plotted as a function of time, a curve similar to Figure 1 will be obtained. A contact time sufficiently long to ensure a reasonable approach to equilibrium should be chosen.

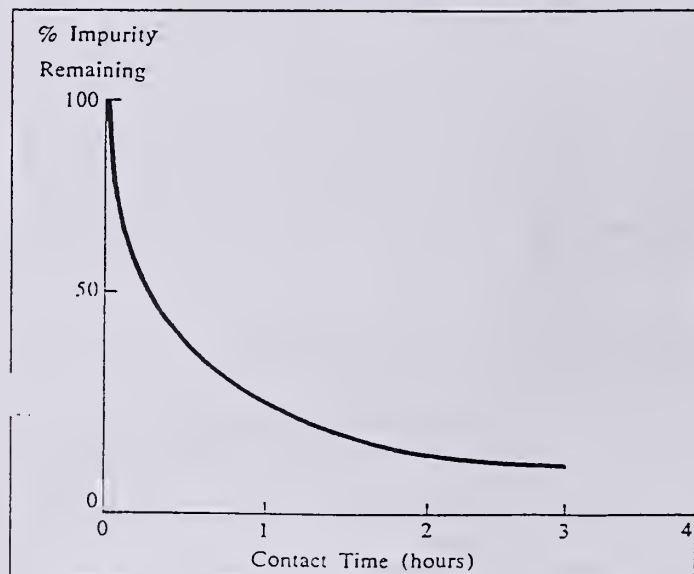


Figure 1 — Contact Time Curve

Effect of pH

Activated carbon may affect the pH of a liquid it contacts either by the dissolution of a portion of its inorganic ash constituents or by the preferential adsorption of acidic or basic ingredients from the solution. Any effect of this kind will be greater at the higher carbon dosages. The final pH of the solution may affect the adsorption equilibrium and in addition may affect the color of the solution. If changes of sufficient magnitude occur to alter the color of the solutions, they should be adjusted to the same pH value as the blank before color readings are obtained.

Also, the pH of the solution being tested may affect the carbon efficiency. Adsorption of organic molecules is generally more efficient at their isoelectric point.

Particle Size of the Carbon

In a liquid-phase application, the transfer of the adsorbate from the bulk solution to the carbon particle must proceed through at least two stages.

1. Transfer of the adsorbate molecule from the bulk liquid to the surface of the carbon particle.
2. Migration of the adsorbate from the surface of the carbon to the adsorption site within the particle.

It is known from kinetic experiments that step 1 is appreciably more rapid than step 2 and the latter is probably the rate determining step. The rate of adsorption then will vary with the diameter of the carbon particles used in the test. In order to eliminate this variable, or at least minimize its effects, it is recommended that the granular carbon be pulverized so that 95% will pass through a 325 mesh screen.

Carbon Dosage

For preliminary trials, dosages of 0.5, 1.0, 2.0 and 5.0 grams per 100 ml. of solution may be used. If the five gram dosage is not sufficient to effect the desired degree of impurity removal, higher dosages should be tried until that degree is attained. If on the other hand, one of the intermediate dosages is sufficient to effect complete or satisfactory purification one or two lower dosages should be tried. In order to obtain a satisfactory isotherm, as wide a range of decolorization as is practical should be obtained.

APPARATUS

Pulverizing

If suitable mechanical equipment, such as a laboratory Ball-mill, is not available, sufficient pulverized carbon for the test work can be obtained from Pittsburgh Activated Carbon Co.

Carbon Treatment

Stoppered flasks or pressure bottles serve as satisfactory containers for the carbon-liquor mixture. Manual agitation even at frequent intervals is usually inadequate and a mechanical shaker is desirable. If a constant temperature bath is used the design of the shaker should be such that it permits immersion

of the lower parts of the containers in the bath, as shown in Figure 2. (A Burrell Wrist Action Shaker, Catalogue No. 75-775, has been found quite suitable in our laboratories.)



Figure 2

Filtration

Either a laboratory pressure filter similar to the Horm Model No. 1 * (Hormann and Company, Newark, New Jersey) or Buchner funnels and filter flasks may be employed.

* Asbestos disks for this pressure filter can be obtained from National Aluminate Corporation, Chicago, Illinois.

Color Determination

Any reliable colorimeter or spectrophotometer may be used. All readings should be made at the same wave length and standardized to constant cell depth. Visual comparison with prepared standards is less accurate but may be used if suitable instruments are not available.

Additional Equipment

In addition to the above list, an analytical balance, an electric drying oven, a pH meter or pH test paper and a delivery burette or graduated cylinders are necessary.

PROCEDURE

1. Pulverize a representative sample of the granular carbon (a 10-20 gram sample is usually adequate) so that 95% will pass through a 325 mesh screen, or use material supplied by Pittsburgh Activated Carbon Company. Oven dry the pulverized sample for three hours at 150°C.
2. Obtain a representative sample of the liquor to be tested. Any suspended matter should be removed by filtration.
3. Transfer four different weights of the oven dried pulverized sample to suitable containers. Sample weights should be chosen in accordance with the suggestions given under Carbon Dosage.

4. To one container add 100 ml. of test liquor from a delivery burette or graduated cylinder, and clamp the container on the shaker. If a constant temperature bath is used, the shaker should be so designed to permit immersion of lower part of the container containing the carbon-liquor mixture in the bath. Agitate the mixture for the chosen contact time. The bottles may be filled and placed on the shaker at ten or fifteen minute intervals to give the analyst sufficient time to filter each sample immediately after the contact time has elapsed and to determine the residual color or concentration. The same volume of liquor should be added to a container without carbon and subjected to the same procedure in order to obtain a blank reading.
5. After the chosen contact time has elapsed, filter the contents of the flask through either a laboratory pressure filter fitted with an asbestos disk or through a Buchner funnel containing a filter paper inserted in a filter flask connected to vacuum. It is desirable to discard the first and last portions of the filtrate and save only the middle portion for analysis. The blank should be filtered in the same manner as the other samples.
6. Determine the color of the filtrate by an accepted method. If the removal of a colorless contaminant is being investigated, the residual concentration can be determined by an alternative analytical procedure.
7. Tabulate the data as shown in Table I. The residual solution color or concentration, c , is obtained directly from the filtrate analysis. The amount adsorbed on the carbon, x , is obtained by subtracting the value of c from that of c_0 , the influent concentration. Dividing x by m , the weight of carbon used in the test gives the amount adsorbed per unit weight of carbon.
8. On log paper plot c on the horizontal axis against x/m on the vertical axis and draw the best straight line through the points, as illustrated in Figure 3.

TABLE I
TREATMENT OF ISOTHERM DATA

m Weight of Carbon (g./100 ml. solution)	c Residual Solution Color	x Color Adsorbed	x/m Color Adsorbed Per Unit Weight
0	7.70	—	—
0.05	3.67	4.03	80.6
0.1	2.20	5.50	55.0
0.3	0.87	6.83	22.8
1.0	0.25	7.45	7.5

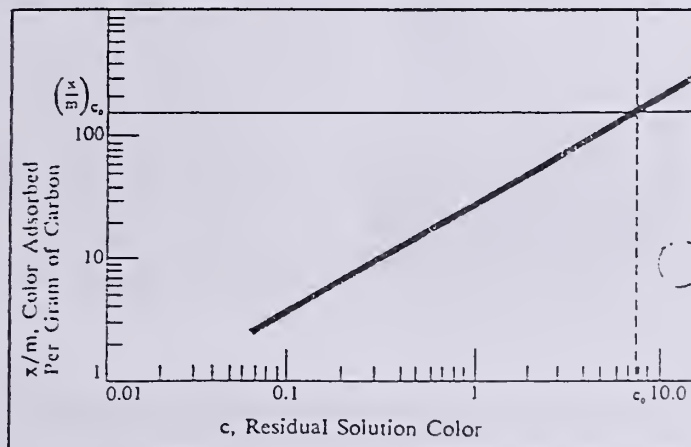


Figure 3 — Typical Decolorization Isotherm

Interpretation of the Isotherm

From the isotherm it is immediately apparent whether or not the desired degree of purification can be attained with the particular activated carbon tested. Considerably more information can be obtained from a more detailed examination.

CALCULATION OF ADSORPTIVE CAPACITY

If a vertical line is erected from the point on the horizontal scale corresponding to the influent concentration (c_0) and the isotherm is extrapolated to intersect that line (Figure 3), the x/m value at the point of intersection can be read from

the vertical scale. This value, termed $\left(\frac{x}{m}\right)_{c_0}$ represents the

amount of impurity adsorbed per unit weight of carbon when that carbon is in equilibrium with the influent concentration. Since this equilibrium should eventually be attained during column treatment, it represents the ultimate capacity of the carbon.

From the value of $\left(\frac{x}{m}\right)_{c_0}$ the capacity in terms of volume of liquid treated can be calculated.

For complete decolorization:

$$V_{c_0} = \frac{\left(\frac{x}{m}\right)_{c_0}}{c_0} \cdot V$$

where V_{c_0} = theoretical volume of liquid decolorized per gram (or unit weight) of carbon

$\left(\frac{x}{m}\right)_{c_0}$ = capacity per gram (or unit weight) of carbon at the influent concentration

V = volume of liquid used in the isotherm test

c_0 = influent concentration

This formula is only applicable when complete decolorization is attained. When the decolorization is not complete or if it is desired to calculate the volume of liquid decolorized to concentration c_1 , the following formula may be used.

$$V_{c_0} = \frac{\left(\frac{x}{m}\right)_{c_0} \cdot c_0}{c_0 - c_1} \cdot V$$

EXAMPLE OF CAPACITY CALCULATIONS

From the example in Table I

$$\left(\frac{x}{m}\right)_{c_0} = 159$$

For complete decolorization

$$V_{c_0} = \frac{159}{7.7} \times 100 = 2065 \text{ ml./g. carbon}$$

For 90% decolorization

$$V_{c_0} = \frac{159}{7.70 - 0.77} \times 100 = 2294 \text{ ml./g. carbon}$$

From these figures, the carbon dosage required to effect a given degree of decolorization may be obtained. For example, the amount of carbon required to completely decolorize one liter of solution is

$$\frac{1}{2065} \times 1000 = 0.48 \text{ grams}$$

COMPARISON OF DIFFERENT CARBONS

The performance of two carbons for the same application can be conveniently compared by examination of the isotherms obtained under identical conditions. Isotherms obtained for two carbons A and B using the same test liquor are plotted in Figure 4. The numbers adjacent to the experimental points indicate grams of carbon used in the test.

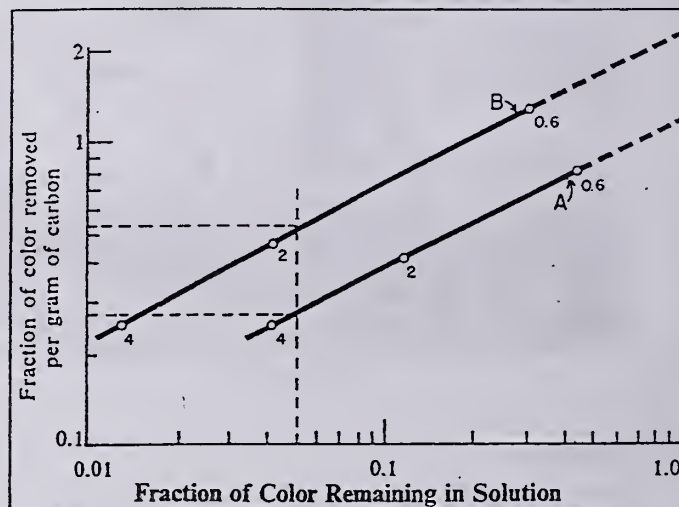


Figure 4 — Parallel Isotherms

The two carbons can be compared at any desired degree of decolorization by drawing a vertical line from that concentration on the horizontal axis and reading the x/m values corresponding to the points of intersection of that line with the isotherms on the vertical axis. Such a line has been drawn at 95% color removal in Figure 4 and the following x/m values are obtained:

$$(x/m)_A = 0.28$$

$$(x/m)_B = 0.52$$

The relative efficiency of carbon A with respect to carbon B can be calculated from the equation.

$$\% \text{ Relative Efficiency (RE)} = \frac{(x/m)_A}{(x/m)_B} \times 100$$

In this case

$$\% \text{ RE} = \frac{0.28}{0.52} \times 100 = 53.8\%$$

Parallel isotherms were obtained in the case illustrated here. Consequently the relative efficiency will be independent of the decolorization effected. If the lines are not parallel, however, the RE will vary with the final concentration at which the comparison is made.

It should be emphasized that highly misleading results can be obtained by making the erroneous assumption that two carbons can be compared for a granular carbon column application by comparing the decolorizations effected by the same dosage of the two carbons.

For example, 4 grams of carbon B effects 98.8% decolorization. The same amount of carbon A effects 96% color removal. On this basis, the carbons appear almost equally efficient. However, in a column operation carbon B will have a capacity almost twice that of carbon A at any degree of decolorization.

In some cases, the isotherms for two carbons will cross as illustrated in Figure 5.

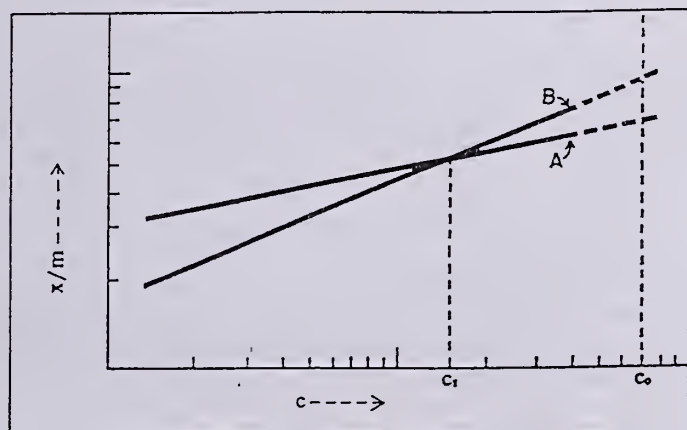


Figure 5 — Crossed Isotherms

Above the point c_i carbon B has a higher capacity than carbon A, below this point the reverse is true. Carbon B would be preferable for column operation because of its higher capacity at the influent concentration. It should be noted, however, that for batch treatment A would be preferable. In general, the steeper the slope of the isotherm exhibited by a particular carbon, the greater will be its efficiency in column operation. This example illustrates the necessity of obtaining isotherms that cover the entire concentration range before comparing two carbons for a particular application.

NON-LINEAR ISOTHERMS

It was noted above that straight lines are obtained when dealing with dilute solutions. Several factors, however, may cause departures from linearity.

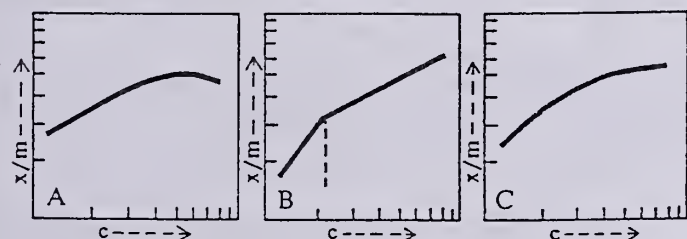


Figure 6 — Non-Linear Isotherms

A curve similar to that shown in A (Figure 6) may be obtained if the solute is appreciably adsorbable or if the color value of the original solution is erroneously low. An erroneously high initial concentration would cause the isotherm to curve upwards. These errors may be due to the concentration of impurity in the blank.

A sudden change in slope illustrated in curve B would indicate that two or more species of color bodies are present not all of which are equally adsorbable. The apparent end point indicated by the dotted line in curve B would indicate the presence of a non-adsorbable impurity. Where the various species do not differ too greatly in adsorbability, a more gradual curvature similar to that shown in C will be obtained.

SUMMARY

From an isotherm test one can determine whether or not a particular decolorization or purification can be effected and obtain an approximation of the ultimate capacity of the carbon for that application. From the capacity figure an estimate of the quantity of carbon necessary for the treatment and consequently rough cost figures can be obtained. Furthermore, isotherm tests afford a convenient method for comparing different carbons and for investigating the effects of pH and temperature.

COLUMN TESTS

Before the column decolorization process can be introduced into a plant or even a pilot plant certain additional information must be obtained. The operating capacity as well as the optimum flow rate and bed depth must be established in order to determine the dimensions and the number of columns necessary for continuous treatment. The flow rate and bed depth necessary for optimum performance will depend upon the rate at which the impurities are adsorbed by the carbon and can only be determined by dynamic column tests.

Apparatus

COLUMNS

Full scale granular carbon columns in general contain beds that are from ten to thirty feet in depth and from one to ten feet in diameter. In the laboratory the diameter of the columns can be scaled down to one or two inches and by an appropriate reduction in flow rate, plant conditions can be simulated. It is impossible, however, to extrapolate the data obtained from a one or two foot bed depth to determine performance in a ten foot bed depth. Consequently, it is highly desirable to conduct the tests in columns that are ten feet in length and preferably longer. Few laboratories can accommodate ten foot columns, but this difficulty may be surmounted by using several five foot sections connected in series. This arrangement is in fact, highly desirable, since effluent samples can be conveniently collected from each five foot section and the effect of bed depth can be investigated.

Apparatus suitable for this type of experiment is available in almost any laboratory as indicated in the following recommendations.

A typical arrangement would be three glass or metal tubes, 4 to 5 feet long, connected in series; the diameter could be any convenient size, but no smaller than 1 inch to avoid excessive wall effect. If operation at elevated temperature is desired, water jackets, electrical windings, infrared lamps or immersion baths can be used.

A column assembled from Pyrex glass pipe is shown in Figure 7.

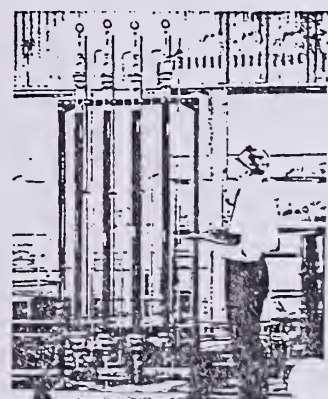


Figure 7—Column Assembly

PUMP

A small pump capable of uniform delivery rates with positive displacement from 0.15 to 1.5 gph is desired, e.g., a gear, diaphragm, centrifugal, piston-type or cam-finger pump.

CONNECTIONS

Rubber, glass, plastic or metal tubing can be used depending upon the corrosion characteristics of the material to be processed. Generally, rubber and glass tubing connections with glass tees and pinch clamps are most convenient.

ARRANGEMENT OF EQUIPMENT

The columns are mounted vertically and connected in series for downflow operation as shown in Figure 8. Provision must be made for taking samples between each column so that decolorization can be studied as a function of bed depth, as well as of time and volume of liquor treated. The carbon bed is retained by a stainless steel screen, glass wool or porous plate at the base of each column. If desired, manometers or pressure gauges can be used to follow the pressure drop characteristics of the operation.

Procedures

COLUMN CHARGING

For laboratory tests in small columns it is best to soak the required quantity of granular carbon to fill the column in the hot liquid to be treated, or in hot water, to expel most of the air from the carbon. The wet carbon is charged in small increments to the column, keeping a thin layer of supernatant liquor during charging. The feed liquor is then admitted to the top of the column after filling the free space with liquor.

In some instances upflow operation is employed. In this case it may be possible to load the columns dry and pump the solution upflow through the dry carbon. If too much heat of adsorption is encountered so that the solution becomes discolored then a suitable solvent should be used first.

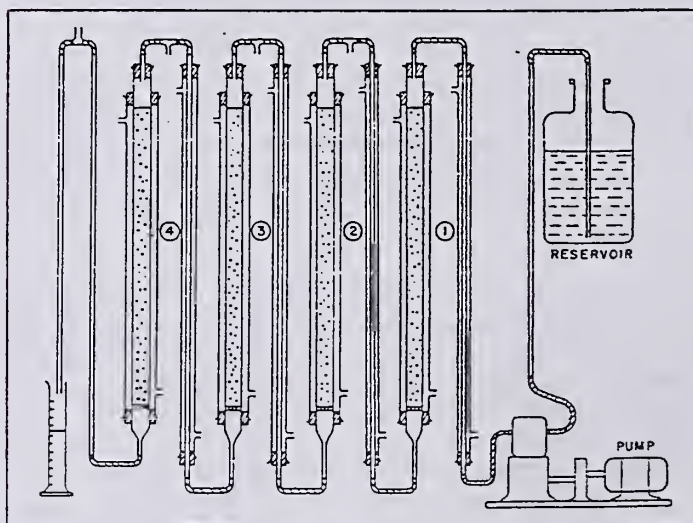


Figure 8 —Laboratory Columns

COLUMN OPERATION

Temperature

Since adsorption capacity is a function of diffusion rate, the columns should be operated at a temperature at which the liquid approaches the fluidity of water and yet will not decompose or form color.

Flow Rate

The feed rate to be used depends upon the diameter of the tube which was selected for the experiment. It has been found that feed rates of 0.5 to 1.0 gpm./ft.² of cross-sectional area are good starting rates for most applications; thus, for preliminary trials it is recommended to begin at the lower limit of this range and then later to gradually increase the rate until the quality of the effluent liquor is no longer acceptable. In terms of column diameters normally used in laboratory work, 0.5 gpm./ft.² of bed area is equivalent to the following rates for a given tube diameter.

TABLE II

TUBE DIAMETER		FLOW RATE FOR 0.5 GPM./FT. ²	
Inch	Centimeter	cc./min.	gph.
1	2.54	10.4	0.164
2	5.08	41.3	0.655
3	7.62	93.5	1.48

Sampling and Analysis

Liquid is pumped through the column system and effluent samples are collected at hourly intervals or at specific volume throughput intervals.

TREATMENT OF THE DATA

If, for any single column of the system used in the experiment the per cent impurity remaining is plotted as a function of throughput volume, a curve is obtained which will vary in form depending on the nature of the system under investigation.

Examples of such curves are shown in Figure 9.

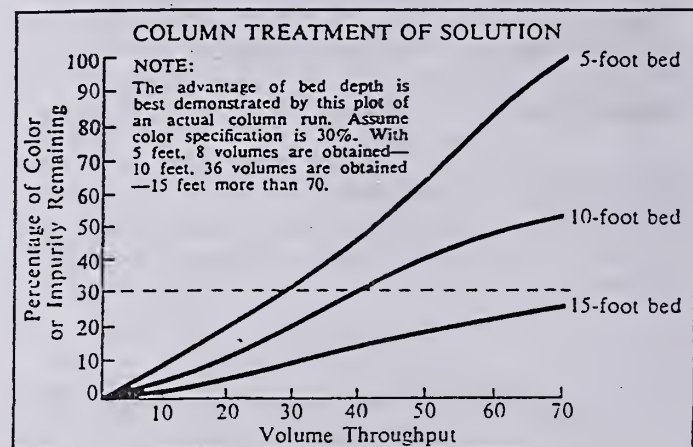


Figure 9 — COLUMN TREATMENT OF SOLUTION

The point at which impurity first appears in the effluent is termed the *break-point*, and that part of the curve between the break-point and the point where the effluent concentration is the same as the influent is called the *breakthrough curve*.

During the adsorption cycle in a column process, the upper section of the bed will be saturated with impurity, the lower section is still free of impurity and between these two extremes lies a zone in which the adsorption is actually taking place sometimes referred to as the mass transfer zone or MTZ. As the column becomes saturated this adsorption zone moves downward through the bed and can be regarded as an adsorption wave front moving through the column. The length of time required for the appearance of the break-point and the shape of the breakthrough curve provides an indication of the relative depth of the adsorption zone. If considerable time

elapses before the break-point appears and the breakthrough curve is sharply defined and steep, the adsorption zone is short relative to the over-all bed depth. If on the other hand breakthrough occurs almost immediately, as it does in Figure 9 at the shorter bed depths, a relatively deep adsorption zone is indicated. The breakthrough curves shown here indicative of a deep adsorption zone were chosen deliberately because they are typical of most liquid phase activated carbon column processes encountered in practice.

By inspection of these curves the volume of acceptable effluent collected at each bed depth investigated can be read directly. Further, the carbon dosage (pounds of carbon used per unit weight or unit volume of product treated for each bed depth) can be calculated. From such data one can see immediately whether advantages can be gained from deep beds.

The effect of flow rate must be considered. In general, increasing the flow rate will lengthen the adsorption zone and reduce the volume of acceptable effluent produced at any given bed depth. The extent to which this occurs, however, must be determined by experiment. Preliminary tests in five foot beds will indicate whether the shape of the breakthrough curves is markedly influenced by flow rate. If marked changes are not found at a higher rate, it may be desirable to determine the complete breakthrough curve in a longer column, at that rate, so that the carbon dosage can be calculated and compared for the two different flow rates.

Having established the flow rate, the diameter of the column or columns necessary to treat the plant throughput can be calculated. From the carbon dosages calculated from the breakthrough curves, it will be apparent whether marked economic advantages can be realized from a deep bed, up to the limit investigated in the test. In many cases this information will be sufficient for preliminary plant design calculations.

In some cases the advantages of the deepest bed used in the test are sufficiently marked that the question immediately arises—what effect will deeper beds have? If the data indicate that deeper beds may be advantageous it is usually wise to consider countercurrent application.

The carbon capacity in a system of this kind can be determined by carrying out the countercurrent procedure in a set of laboratory columns for several cycles. The carbon dosage can then be calculated from the weight of liquor processed during each cycle and the weight of carbon required to fill a single column. Dosages determined in this way can be compared with those obtained for a single column.

Consider a system in which the liquid to be treated is percolated through a series of three columns. After a certain period has elapsed the carbon in the first column of the series will be saturated with the particular colorants or impurities involved while the second and third columns are still adsorbing these contaminants. At this point the first column can be removed from service and a fourth column installed in the number three position. The former second and third columns now become the first and second in the new series. This procedure can be continued indefinitely and affords an excellent method for utilizing the maximum adsorptive capacity of the carbon.

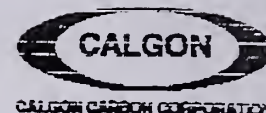
In conclusion, it should be emphasized that in many cases there will be a number of different ways in which a column system for a given application can be operated. Unfortunately short cut methods for designing the optimum system are not available. The relative advantages of each method can be ascertained only by carefully working through the problem, keeping in mind the particular requirements of the process.

You are encouraged to contact Pittsburgh Activated Carbon Company for data prior to setting up testing programs. As an experienced producer of Activated Carbon for over 20 years, varied and extensive data is available for use in establishing test program guidelines.



PITTSBURGH ACTIVATED CARBON
DIVISION OF CALGON CORPORATION
SUBSIDIARY OF MERCK & CO., INC.

CALGON CENTER, BOX 1346, PITTSBURGH, PA. 15230

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Plus General References .

Groundwater Contamination

Table 3
Operating Results—Influent Contaminants at mg/l Levels

System No.	Source of Contaminants	Contaminants	Typical Influent Conc. (mg/l)	Typical Effluent Conc. (ug/l)	Flow per Train (gpm)	Surface Loading (gpm/ft ²)	Total Contact Time (min.)	Carbon Usage Rate (lb./1,000 gal.)	Carbon Type	Carbon System Pre-treatment	Carbon System Back-Washable	Operating Mode	Disposition of Effluent
1	Truck spill	Methylene chloride 1,1,1-Trichloroethylene	21 25	<1.0 <1.0	20	0.25	534	2.9	Reactivated	None	No	2 beds in series	Discharge to surface water
2	Rail car spill	Phenol Dichlorodiphenyl ether	63 100	<1.0 <1.0	20	1.0	201	2.5	Reactivated	Filtration	No	3 beds in series	Discharge to surface water
3	Rail car spill	Phenol Vinylidene chloride	22-40 2-4	<10.0 <10.0	875 Tr 175	2.2	60	2.1	Reactivated	None	No	2 beds in series	Discharge to surface water
4	Rail car spill	Ethyl acetate	200	<1.0	300 Tr 100	2.0	52	13.5	Reactivated	Filtration	No	3 beds in series	Discharge to surface water
5	Chemical spill	Chloroform Carbon tetrachloride Trichloroethylene Tetrachloroethylene	5.4 120-125 2.0 70	<1.0 <1.0 <1.0 <1.0	40	0.5	282	11.8	Reactivated	None	No	2 beds in series	Process water
6	Chemical spill	Chloroform Carbon tetrachloride Trichloroethylene Tetrachloroethylene	0.6 10.0 0.6 10-20	<1.0 <1.0 <1.0 <1.0	160	2.5	56	2.8	Reactivated	None	No	2 beds in series	Process water
7	On-site storage tanks	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	0.5 1.0 7.0	<1.0 <1.0 <1.0	155	2.1	54	0.8	Virgin FS-300	None	@ Installation only	2 beds in series	Process and potable use
8	On-site storage tanks	Methylene chloride 1,1,1-Trichloroethane	1.5 3.0	<100 <1.0	20	0.20	520	4.2	Reactivated	None	No	2 beds in series	Discharge to surface water
9	Chemical spill	Dichloroethyl ether Dichlorodipropyl ether	1.1 0.8	<1.0 <1.0	2200 Tr 750	9.8	18	0.45	Reactivated	None	Yes	2 beds in series	Process and potable use
10	Chemical spill	Benzene Tetrachloroethylene	0.4 4.5	<1.0 <1.0	95	1.21	112	1.8	Reactivated	None	No	2 beds in series	Discharge to surface water
11	Landfill site	TDC Chloroform Carbon tetrachloride Etc., etc.	20 1.4 1.0 14.0	<0.5 mg/l <1.0 <1.0 <1.0	20	1.0	41	1.55	Reactivated	Filtration	No	Dual mini in series	Discharge to surface water
12	Gasoline spill	Benzene Toluene Xylene	9-11 6-7 6-10	<100 Total	5	0.4	214	<1.01	Virgin FS-300	None	No	Dual mini in series	Discharge to surface water
13	On-site storage tanks	Trichloroethylene Xylene Isopropyl alcohol Acetone	0.6 2.6 2 .1	<1.0 <1.0 <10.0 <10.0	30	2.4	38	1.54	Reactivated	None	No	Dual mini in series	Ground recharge
14	On-site storage tanks	1,1,1-Trichloroethane 1,2-Dichloroethylene Xylene	12 0.5 8.0	<5.0 <1.0 <1.0	200	2.5	52	1.0	VR	None	No	2 beds in series	Discharge to sewer
15	Chemical spill	DSCP	2.5	<1.0	220	3.2	21	0.7-8.0	Virgin FS-300	Filtration	No	1 bed upflow	Ground recharge
16	On-site well storage tanks	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	0.2 0.5 2.0	<1.0 <1.0 <1.0	150	1.81	70	0.75	Virgin FS-300	None	No	3 beds in series	Process and potable use
17	Chemical by-product	Dichloropropyl methyl phosphonate Dichloropropylamine	1.25 0.43	<50 <10	175	2.3	30	0.7	Reactivated	Filtration	No	1 bed	Groundwater recharge
18	Manufacturing residues	DGT TOC 1,2-Dichloropropane	0.004 8.0 0.01	<0.5 <1.0 <1.0	100	2.0	31	1.1	Reactivated	Filtration	Yes	1 bed	Discharge to surface water
19	Chemical spill	1,1,1-Trichloroethane Carbon tetrachloride Trichloroethylene Tetrachloroethylene	0.82 0.484 3.877 6.800	<10 Each Comp.	200	2.5	53	1.5	Reactivated	None	No	2 beds in series	Discharge to surface water
Median Levels								50	1.54				

This value represents total volume of liquid being treated with granular activated carbon at this site.

Table 4
Operating Results—Influent Contaminants at ug/l Levels

System No.	Source of Contaminants	Contaminants	Typical Influent Conc. (ug/l)	Typical Effluent Conc. (ug/l)	Flow per Train (gpm)	Surface Loading (gpm/ft ²)	Total Contact Time (min.)	Carbon Usage Rate (lb./1,000 gal.)	Carbon Type	Carbon System Pre-treatment	Carbon System Back-Washable	Operating Mode	Disposition of Effluent
1	Solvent spill	1,1,1-Trichloroethane Trichloroethylene Tetrachloroethylene	140 8.4 29	<1.0 <1.0 <1.0	300	4.6	16	0.40	Virgin FS-300	None	@ Installation only	1 bed	Potable use
2	Gasoline tank leakage	Methyl T-Butyl Ether Diisopropyl Ether Trichloroethylene Chloroform	20-35 20-40 55-60 200-200	<5.0 <1.0 <1.0 <1.0	450	5.7	12	0.62	Virgin FS-300	None	Yes	2 beds in parallel	Potable use
3	On-site storage tanks	Trichloroethylene	6-10	<1.0	200	2.5	26	1.12	Virgin FS-300	None	@ Installation only	4 beds in parallel	Process and potable use
4	Rail car spill	Chloroform	20	<1.0	30	0.6	160	7.7	Reactivated	Air strip	No	1 bed	Discharge to surface water
5	On-site storage tanks	Trichloroethylene	20-200	<1.0	200	4.6	20	0.40	Virgin FS-300	Filtration	No	2 beds in series	Potable use
6	Chemical solvents	Trichloroethylene Tetrachloroethylene	20-40 140-200	<1.0 <1.0	200	5.3	21	0.21	Virgin FS-300	Air strip	Yes	3 beds in parallel	Potable use
7	Chemical landfill	1,1,1-Trichloroethane 1,1-Dichloroethylene	20-40 0-15	<1.0 <1.0	200	4.6	30	<0.45	Virgin FS-300	None	Yes	2 beds in series	Potable use
8	Gasoline tank leakage	Trichloroethylene Diisopropyl Ether	40-60 20-30	<1.0 <1.0	450	5.7	12	0.10	Virgin FS-300	Air strip	Yes	3 beds in parallel	Potable use
9	Chemical solvents	Trichloroethylene CIS-1,2-Dichloroethylene	20-25 10-15	<1.0 <1.0	180	2.0	25	<0.32	Virgin FS-300	None	@ Installation only	1 bed	Potable use
10	On-site storage tanks	Trichloroethylene	60	<1.0	250	1.8	42	0.38	Virgin FS-300	None	No	2 beds in parallel	Potable use
11	Chemical spill	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	5 5 10	<1.0 <1.0 <1.0	95	1.1	121	0.25	Virgin FS-300	None	No	2 beds in series	Potable use
12	Chemical spill	CIS-1,2-Dichloroethylene Trichloroethylene Tetrachloroethylene	5 5 10	<1.0 <1.0 <1.0	160	1.91	70	0.25	Virgin FS-300	None	No	2 beds in series	Potable use
Median Levels								30	0.25				

**CALGON CARBON CORPORATION
EXPERIENCE REFERENCE****REPORTED
JANUARY, 1989****SITE IDENTIFICATION:**

Potable Groundwater Treatment System
Groveland Well No. 1
Groveland, Massachusetts

SITE DESCRIPTION:

In August, 1986, Calgon Carbon Corporation provided an adsorption system consisting of two adsorbers to be operated in series to treat contaminated groundwater from Groveland Well No. 1. The system consists of two units, each containing 20,000 lbs. of Granular Activated Carbon to treat 400 gpm. The system is designed for series operation, either unit which is capable of being in the lead or first stage position. Each adsorber is also capable of being backwashed in order to maintain operation of the carbon on-line despite a possible buildup of solids.

The adsorption system was bid and provided to Camp, Dresser & McKee, Inc., who was prime contractor to the US Environmental Protection Agency (EPA) under provisions of an REM II Contract. The Groveland Wells (No. 1 and 2) are the sole source of drinking water for the town of Groveland, and upon detection of contamination by trichloroethylene, 1,1,1-trichloroethane, 1,2-dichloroethylene, toluene and chloroform were shut down and subsequently identified as a National Priority List Site. Under contract to the EPA, CDM provided for the remediation of the site.

Calgon Carbon bid the adsorption system to CDM in March of 1986, and after a brief delay, had the system installed and operation in August. The contamination at the Groveland Well No. 1 has dropped significantly from design values, and the current system carbon usage rate is undetermined.

CALGON CARBON CORPORATION
EXPERIENCE REFERENCE

(CONTINUED)

REPORTED
JANUARY, 1989

SITE IDENTIFICATION:

Potable Groundwater Treatment System
Groveland Well No. 1
Groveland, Massachusetts

SYSTEM DESIGN PARAMETERS:

System Design:	2 Adsorbers, Series Operation
Adsorber Size:	10 ft. diameter x 14 ft. side
GAC Amount & Type:	20,000 lb. Calgon Carbon Filtrisorb 300 per adsorber
Flow:	400 gpm
Contact Time:	26 minutes (Empty Bed or 'EBCT' basis)
Contaminants: (Design Basis)	Trichloroethylene 400 ppb T-1,2-Dichloroethylene 100 ppb 1,1,1-Trichloroethane 50 ppb Tetrachloroethylene 30 ppb 1,1-Dichloroethane 10 ppb Toluene 10 ppb
Performance:	Total VOCs < 5 ppb Trichloroethylene < 2.5 ppb
References:	Mr. Richard Christian, Proj. Mgr. Camp, Dresser & McKee One Center Plaza Boston, MA 02108 (617-742-5151) Mr. James Cirillo, Proj. Mgr. US EPA JFK Federal Building Boston, MA 02203 (617-565-3715)

**CALGON CARBON CORPORATION
EXPERIENCE REFERENCE****REPORTED: August, 1987
UPDATED: January, 1992****SITE IDENTIFICATION:**

Potable Groundwater Treatment System
Department of Public Works
Town of Marshfield, Massachusetts

SITE DESCRIPTION:

In 1987, Calgon Carbon Corporation provided a Model 10 Adsorption System to treat contaminated drinking water from the Furnace Brook No. 1 Well located in Marshfield, Massachusetts. The adsorption system consists of two adsorbers to treat up to 700 gpm in a parallel operation (350 gpm per adsorber). The adsorbers may be backwashed from the potable water system if required. The Model 10 System is a packaged adsorption plant, consisting of two adsorbers and all system piping installed on a steel skid.

In early 1987, the Town of Marshfield discovered that some of their water supply wells were contaminated with perchloroethylene, chloroform and toluene. The Town closed the contaminated wells and instituted water bans to conserve water while utilizing uncontaminated wells. GHR Engineering Associates, Inc., of Lakeville, Massachusetts, assessed the contamination and prepared a specification for a granular activated carbon (GAC) treatment plant for the Furnace Brook No. 1 Well site. Calgon Carbon bid the treatment system to the Town of Marshfield on April 30, 1987, and received the Notice of Award on June 2, 1987.

The GAC system was delivered and installed by Calgon Carbon within four weeks due to standard design and modular construction. A booster pump was added on the GAC system effluent to allow direct discharge into the potable water distribution system. The Furnace Brook No. 1 Well was put back into operation by July 1, 1987.

SYSTEM DESIGN PARAMETERS:

System Design:	2 Adsorbers, Parallel Operation
Adsorber Size:	10 ft. diameter x 14 ft. side
GAC Amount & Type:	20,000 lb. Calgon Carbon Filtrisorb 300 per adsorber
Flow:	700 gpm (350 gpm per adsorber)
Contact Time:	15 minutes (Empty Bed or 'EBCT' basis)
Contaminants:	Perchloroethylene up to 30 ppb
Performance:	PCE, Chloroform at <1 ppb (non-detectable)
GAC Usage Rate:	0.15 lbs./1,000 gallons (estimate)
Reference:	Mr. Carl Hillstrom Water & Sewer Supervisor Department of Public Works 870 Moraine Street Marshfield, MA 02050 617-834-5575

APPENDIX D

SELECTED PARAMETERS FOR THE WASTE WATER TREATMENT SYSTEM

FILE: SD-5A.CWD

10-28-1996 07:02:39

UNIT: General specifications _____	
Wind velocity (cm/s at 10 m)	447
Wastewater temperature (C)	11.7
Wastewater flow rate (m3/s)	.0284
total dissolved organics in (mg/l)	1.2
inlet suspended solids	2.5
Overall biorate (mg/g bio-hr)	0

UNIT: storage tank _____	
number units in parallel	1
Wastewater temperature (C)	11.7
Open surface area of tank (m2)	0
Density of liquid in tank (g/cc)	1
tank waste Mwt, water=18	18
tank storage time (days)	.035494
tank paint factor	1
tank diameter (m)	4.2672
tank vapor space height (m)	2
diurnal temp. change (°C)	11
tank height (m)	6.096
oil in composite wastewater (vol %)	0
Recycle flow out of unit (m3/s)	0

INLET COMPOUND CONCENTRATIONS _____

ETHYLBENZENE	.002 ppmw
TETRACHLOROETHENE	.00114 ppmw
TOLUENE	.0008 ppmw
XYLENE	.004 ppmw

SOURCE: storage tank Version 4
COMPOUND: ETHYLBENZENE

tank storage time (days)	0.0355
Tank turnover factor	0.1696
Tank working loss (fraction)	0.0245
Tank breathing loss (fraction)	0.6050E-02
TOTAL AIR EMISSIONS (g/s)	0.1724E-05
(Mg/year)	0.5437E-04
EMISSION FACTOR (g/cm2-s)	0.1206E-10
UNIT EXIT CONCENTRATION (ppmw)	0.1939E-02

WASTEWATER TREATMENT SUMMARY: ETHYLBENZENE Version 4

SD-5A.CWD 10-28-1996 07:02:40

COMPOUND PROPERTIES OF ETHYLBENZENE at 25 deg. C

Type of compound	A aromatic	
density (g/cc)		.87
molecular weight		106.2
diffusion coef. water (cm ² /s)		.0000078
diffusion coef. air (cm ² /s)		.075
vapor pressure (mm Hg)		10
Henry's law constant (atm-m ³ /mol)		7.880605E-03
vapor pressure temp. coefficients		6.975
		1424.255
		213.21
zero order biorate constant (mg/g-hr)		6.8
first order biorate constant (1/g-hr)		2.1
octanol water partition coefficient		3.15
UNIFAC code		31=115:0000000
The estimated vapor pressure is 9.88 mm Hg.		

SUMMARY OF AIR EMISSIONS FROM UNITS Version 4

SOURCE	RATE (grams/sec)	Fraction Air	Fraction Remaining	est. conc (ng/m ³)
storage tank	1.724077E-06	0.0304	0.9696	0.102E+03
TOTALS, ALL UNITS	1.724077E-06	0.0304	0.9696	
total fraction absorbed			0	

SOURCE: storage tank Version 4
COMPOUND: TETRACHLOROETHENE

tank storage time (days)	0.0355
Tank turnover factor	0.1696
Tank working loss (fraction)	0.0559
Tank breathing loss (fraction)	0.0148
TOTAL AIR EMISSIONS (g/s)	0.2263E-05
(Mg/year)	0.7137E-04
EMISSION FACTOR (g/cm ² -s)	0.1582E-10
UNIT EXIT CONCENTRATION (ppmw)	0.1060E-02

WASTEWATER TREATMENT SUMMARY: TETRACHLOROETHENE Version 4

SD-5A.CWD 10-28-1996 07:02:41

COMPOUND PROPERTIES OF TETRACHLOROETHENE at 25 deg. C

Type of compound	C chlorinated	
density (g/cc)		1.624
molecular weight		165.83
diffusion coef. water (cm ² /s)		.0000082
diffusion coef. air (cm ² /s)		.072
vapor pressure (mm Hg)		19
Henry's law constant (atm-m ³ /mol)		.0177003
vapor pressure temp. coefficients		6.976
		1386.92
		217.53
zero order biorate constant (mg/g-hr)		6.2
first order biorate constant (l/g-hr)		.68
octanol water partition coefficient		2.6
UNIFAC code		2194v0000000000
The estimated vapor diffusion coefficient is	.0318	cm ² /s
The estimated vapor pressure is	18.088	mm Hg.

SUMMARY OF AIR EMISSIONS FROM UNITS Version 4

SOURCE	RATE (grams/sec)	Fraction Air	Fraction Remaining	est. conc (ng/m ³)
storage tank	2.263159E-06	0.0699	0.9301	0.134E+03
TOTALS, ALL UNITS	2.263159E-06	0.0699	0.9301	
total fraction absorbed			0	

SOURCE: storage tank Version 4
COMPOUND: TOLUENE

tank storage time (days)	0.0355
Tank turnover factor	0.1696
Tank working loss (fraction)	0.0218
Tank breathing loss (fraction)	0.7144E-02
TOTAL AIR EMISSIONS (g/s)	0.6531E-06
(Mg/year)	0.2060E-04
EMISSION FACTOR (g/cm ² -s)	0.4567E-11
UNIT EXIT CONCENTRATION (ppmw)	0.7770E-03

WASTEWATER TREATMENT SUMMARY: TOLUENE Version 4

SD-5A.CWD 10-28-1996 07:02:42

COMPOUND PROPERTIES OF TOLUENE at 25 deg. C

Type of compound	A aromatic	
density (g/cc)		.87
molecular weight		92.4
diffusion coef. water (cm ² /s)		.0000086
diffusion coef. air (cm ² /s)		.087
vapor pressure (mm Hg)		30
Henry's law constant (atm-m ³ /mol)		6.420124E-03
vapor pressure temp. coefficients		6.954
		1344.8
		219.48
zero order biorate constant (mg/g-hr)		73.48
first order biorate constant (1/g-hr)		2.4
octanol water partition coefficient		2.69
UNIFAC code		25:1<000000000
The estimated vapor pressure is 28.348 mm.Hg.		

SUMMARY OF AIR EMISSIONS FROM UNITS Version 4

SOURCE	RATE (grams/sec)	Fraction Air	Fraction Remaining	est. conc (ng/m ³)
storage tank	6.531052E-07	0.0287	0.9713	0.386E+02
TOTALS, ALL UNITS	6.531052E-07	0.0287	0.9713	
total fraction absorbed			0	

SOURCE: storage tank Version 4
COMPOUND: XYLENE

tank storage time (days)	0.0355
Tank turnover factor	0.1696
Tank working loss (fraction)	0.0209
Tank breathing loss (fraction)	0.4356E-02
TOTAL AIR EMISSIONS (g/s)	0.2862E-05
(Mg/year)	0.9025E-04
EMISSION FACTOR (g/cm2-s)	0.2001E-10
UNIT EXIT CONCENTRATION (ppmw)	0.3899E-02

WASTEWATER TREATMENT SUMMARY: XYLENE Version 4

SD-5A.CWD 10-28-1996 07:02:44

COMPOUND PROPERTIES OF XYLENE at 25 deg. C

Type of compound	A aromatic	
density (g/cc)		1.02
molecular weight		106.2
diffusion coef. water (cm ² /s)		9.34E-06
diffusion coef. air (cm ² /s)		.0714
vapor pressure (mm Hg)		8.5
Henry's law constant (atm-m ³ /mol)		5.250005E-03
vapor pressure temp. coefficients		6.68822
		1573.076
		273.16
zero order biorate constant (mg/g-hr)		40.8
first order biorate constant (1/g-hr)		1.8
octanol water partition coefficient		3.15
UNIFAC code		24:2<0000000000
The estimated vapor pressure is 25.764 mm Hg.		

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SUMMARY OF AIR EMISSIONS FROM UNITS Version 4

SOURCE	RATE (grams/sec)	Fraction Air	Fraction Remaining	est. conc (ng/m ³)
storage tank	2.86183E-06	0.0252	0.9748	0.169E+03
TOTALS, ALL UNITS	2.86183E-06	0.0252	0.9748	
total fraction absorbed			0	

WASTEWATER TREATMENT SUMMARY SD-5A.CWD 10-28-1996 07:02:45

COMPOUND	RATE (g/s)	Fraction Air	Fraction Bio	Fraction Remain
ETHYLBENZENE	0.1724E-05	0.03035	0.00000	0.9696
TETRACHLOROETHENE	0.2263E-05	0.06990	0.00000	0.9301
TOLUENE	0.6531E-06	0.02875	0.00000	0.9713
XYLENE	0.2862E-05	0.02519	0.00000	0.9748
TOTAL ALL COMPOUNDS	0.7502E-05			

Storm Drain - 5 Contaminant Loads

Design Flow rate = 450gpm

Contaminant	Wght. Estimate ppb	Current Design ppb	Hot Spot ppb
1,2-Dichloroethene	-	-	1.2
Benzene	-	0.78	4.5*
Bis(2-Ethylhexyl) phthalate	-	-	20
EDB	-	1.1	0.02*
Ethylbenzene	2	-	37.5*
Iron	243	243	-
Lead	-	-	-
Manganese	44	44	120*
Methylene Chloride	-	0.35	6*
Tetrachloroethene	1.14	-	0.74*
Toluene	.8	-	6.61*
Trichloroethene	BQL	3.8	0.9*
Xylene	4	-	124*

*Values from groundwaters that could be drawn in by the recovery wells

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APPENDIX E

IRON AND MANGANESE REMOVAL

Post-It® Fax Note (FYI) 7671		Date	6/27/96	# of pages	6
To	MIKE BRADFORD		From	MARK WILSON	
Co./Dept.	JACOBS		Co.	NEWMAN	
Phone #			Phone #	981-7448	
Fax #	669-3310		Fax #		

Iron and manganese have long been recognized as objectionable in municipal and industrial water supplies, causing taste, stain, color, and turbidity problems. The USPHS (United States Public Health Service) recommended limit for iron is 0.3 mg; for manganese 0.05 mg; and for combined iron and manganese 0.3 mg.

Methods for removal of iron and manganese are dependent upon the comparative insolubility of the hydrated ferric and manganic oxides. Treatment of ground waters (well water) for iron and manganese removal employs an oxidant(s) to form precipitates and filtration to remove the particulate matter.¹ This treatment is normally accomplished by

one of three processes (1) aeration-filtration, (2) chlorination-filtration, or (3) the Manganex Process (Manganese Greensand).

AERATION FILTRATION

Aeration-filtration closely parallels the natural phenomenon of oxidation in ground waters. The process equipment typically includes an aerator, retention tank and filter. (See Figure 1).

An aerator mechanically brings the water in contact with the atmosphere. The oxygen from the atmosphere reacts with the iron and manganese in the raw water, producing relatively insoluble salts of ferric and man-

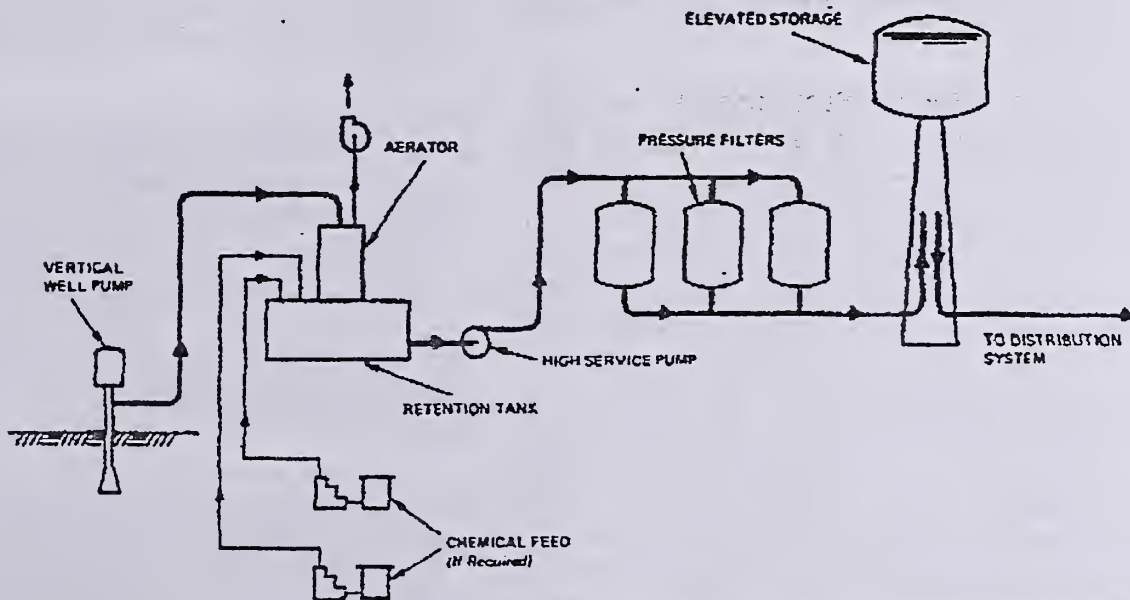


FIG. 1. Typical flow diagram of an aeration-filtration system.



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ganic oxides. Oxygen requirements to convert iron from the ferrous to the ferric state are low, being only 0.14 mg of oxygen for each 1.0 mg of iron. The rate of reaction is dependent upon p, the rate being more rapid at higher pH's. For most waters a 50% saturation of dissolved oxygen is adequate to complete the reaction.

Aeration also reduces the free carbon dioxide, methane and hydrogen sulfide. Sulfide removal is limited by the relatively high pH levels normally encountered in ground water. If complete removal is required, the pH of the water must be in the range of 4 to 5 and be followed by chlorination or potassium permanganate feed. In such cases it is necessary to supersaturate the water with air.

Dissolution of oxygen and expulsion of gases may be accomplished by various aeration devices such as Induced Draft, Forced Draft, Cascade, Coke Tray, and Tray Aerators. Common to all these units is the exposure of drops of water to the atmosphere. (Consult Roberts Filter Manufacturing Co. or a Roberts Representative for application, sizing, and selection).

To allow sufficient reaction time, and also to provide a wet well, aerators are normally followed by retention tanks. Detention time requirements vary from 20 minutes to 3 hours, depending upon characteristics of the raw water.² Retention tanks also serve as an application point for chemical additives such as chlorine, lime, or caustic soda. Treated water is then pumped from the retention tank through pressure filters. If total iron and manganese concentration in the raw water exceeds 7.0 mg, to reduce filter loading, consideration should be given to a sedimentation basin (gravity clarifier) with sludge collection and removal facilities rather than a simple retention tank.

Iron and manganese removal filters are normally of the pressure type. The filter media is either filter sand or a dual bed of anthracite and filter sand. The choice of media is determined by bed loading requirements. In cases where iron and manganese concentrations are low (1.5 mg or less), normally filter sand is sufficient. However, when maximum efficiency in bed loading is required, dual media should be employed. (See Roberts Technical Bulletin 700.2)

CHLORINATION FILTRATION

This process utilizes chlorine (either gas or hypochlorites) as the oxidizing agent. The process equipment normally consists of a chemical feed system and filters. (See Fig.2)

Chlorine is injected into the raw water feed line as close to the well pump as possible to obtain maximum contact time (a minimum contact time of 20 seconds is required). In order for the reaction to take place the chlorine must first react with water to form hypochlorous acid, the active oxidizing agent. The hypochlorous acid reacts with the soluble iron and manganese, producing the respective insoluble oxides.

The theoretical amount of chlorine required to oxidize 1.0 mg of soluble iron is 0.66 mg. In practice, however, more than theoretical quantities are applied. The oxidation reactions are dependent upon, and are more rapid at, higher pH levels. Alkalies, such as soda ash, caustic soda, or lime are used to raise pH to the desired level (see Roberts Technical Bulletin 900.1).

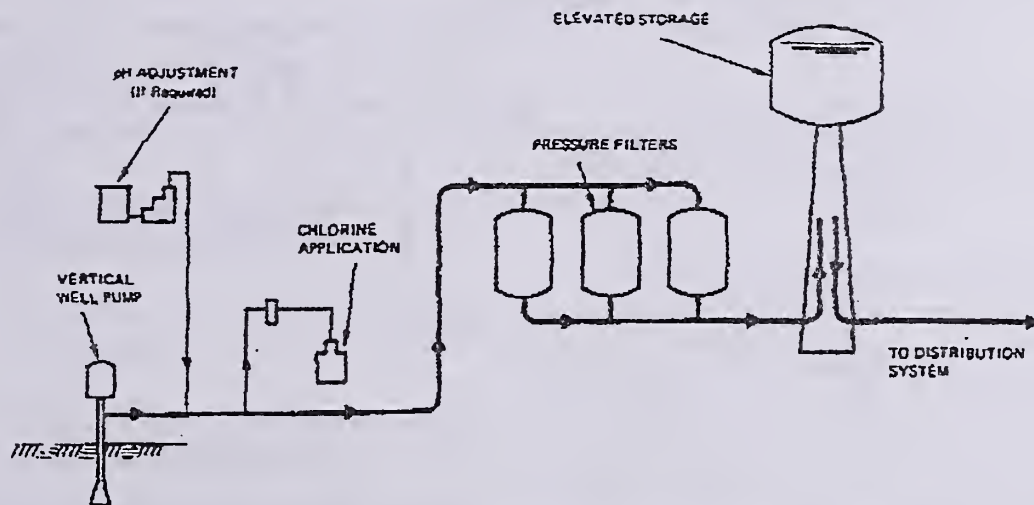
To oxidize each 1.0 mg of soluble manganese theoretically requires 1.3 mg of chlorine. As this reaction is often slow and incomplete, the chlorination-filtration process is normally applied to only iron bearing waters.³



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FIG. 2. Typical flow diagram of a chlorination-filtration system.



After chlorination, and the addition of alkalinity (if required), water is applied directly to the filters and the now insoluble iron is removed by the filter media. Manganese removal is usually minimal (approximately 10% to 20%) unless unusually long contact time is provided.⁴

As with aeration-filtration, the filter media is either filter sand or anthracite and filter sand. In that chlorination-filtration systems are usually used for removal of relatively low concentrations of iron (less than 2 mg), filter sand is often adequate to obtain desired service runs.

MANGANEX PROCESS (MANGANESE GREENSAND)

The Manganex Process (commonly called Manganese Greensand) Flow Diagram is similar to that of chlorination-filtration (see also Figure 3). Equipment requirements for both systems are the same, that is, chemical feed for oxidation, pH adjustment if required,

and a filtration system. The dissimilarities are the primary oxidizing agent and the filter media.

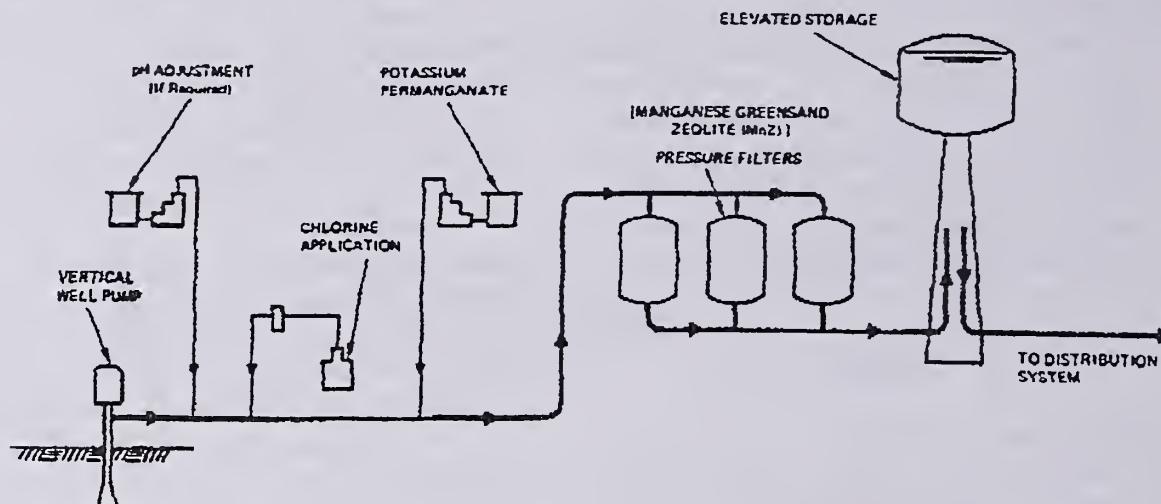
A 1% to 4% solution of potassium permanganate (KMnO_4), a strong oxidizing agent, is fed upstream of the filters to allow a minimum contact time of 20 to 60 seconds.⁵ During this period, soluble iron and manganese are converted to the corresponding oxides. These oxides are removed by an efficiency dual filter media bed composed of a top layer of anthracite and a lower layer of Manganese Greensand. The majority of particulate matter is removed in the anthracite bed. Iron and manganese not removed in the anthracite bed. Iron and manganese not removed by the anthracite are filtered out by the bed of Manganese Greensand. The Greensand will also remove small amounts of iron, manganese and potassium permanganate that remain in the soluble form. This system differs from a normal dual bed in that the Manganese Greensand acts as a "catalyst" removing by chemical as well as physical means.



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FIG. 3. Typical flow diagram of Manganex System.



Potassium permanganate has been used for some time in water treatment but has had a relatively short history as a continuously fed oxidant in pressure filter systems. A problem in the past was the necessity of accurate chemical feed. If too little potassium permanganate were fed, iron and manganese breakthrough would occur. If too much were fed, the KMnO_4 , which had failed to react, would cause a pink color in the filter effluent. This operating problem was greatly reduced by Manganese Greensand.

Manganese Greensand is prepared by treating glauconite (natural zeolite) with manganous sulphate and potassium permanganate which gives this media the characteristics of a catalyst. The treated Greensand acts (when used in conjunction with potassium permanganate) as a buffer zone, compensating for both over or under chemical feeding.

Stoichiometrically, 0.94 mg of potassium permanganate is required to oxidize 1.0 mg of iron, and 1.95 mg of KMnO_4 to oxidize 1.0 mg of manganese. Under normal operating con-

ditions experienced in water treatment the actual requirements are less than these theoretical dosages. At pH levels between 7.5 and 9.0, the reaction is complete and rapid.⁶ The rate of this reaction is very important as this process is usually employed in installations with direct pumping, i.e., from the well through the filters to the distribution system, limiting contact time.

As previously discussed, chlorine is a very effective oxidant for soluble iron. Accordingly, both chlorine and potassium permanganate are employed in contact catalyst filtration when iron appears in significant concentrations (typically greater than 1.0 mg). As most potable water supplies are required to chlorinate for sterilization, prechlorination for oxidation of iron does not increase the capital or operating cost of a water treatment plant.

In certain situations prechlorination is not practical because of the presence of organics, which may form chloro derivatives resulting in objectionable tastes and odors. In such cases, potassium permanganate should



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be employed as the sole oxidizing agent and chlorine should be applied only after filtration.⁷

SYSTEM DESIGN

General, iron and manganese removal systems employ pressure filters. Information regarding these filters may be found Roberts Technical Bulletin 700.

Standard accessory components of iron and manganese removal filters are:

1. Rotary media agitator (for filters larger than 5' Dia.).
2. Roberts non-clog interface airwash system (for filters less than 5' Dia.).
3. Filter rate-of-flow meter to indicate the flow of water during filtering and/or backwashing.
4. Backwash rate-of-flow control device.
5. Sight glasses on waste connections to indicate visual characteristics of waste and rinse water.
6. Sample cocks immediately before and after filter media and chemical feed.

The above are suggested to assure efficient long term operation.

Selection of the most economical iron and/or manganese removal system is based upon raw water characteristics, required effluent quality, and cost analysis (Table 1). In cases where little is known of the aquifer, pilot studies should be considered. Pilot filter systems are available from Roberts on a rental basis for the three processes described in this bulletin. Data from such test programs enable

the designer to determine the best process or a particular project. Where pilot studies are impracticable, jar tests should be used. (Roberts will supply jar test procedure upon request). Experience, of course, is the best guide for any particular area.

After a process has been selected, the proposed system must be examined in terms of chemical feed, hydraulics, and backwash requirements.

System design should provide chemical feed proportional to raw water flow rates. In "on-off" situations where single well pumps are used, control of the chemical feed systems may be inter-connected with the well pump. Often, however, more than one pump will be used producing varying flows. In such cases, either separate chemical feed or each well pump or a variable chemical metering system paced with the raw flow should be employed.

Although important to all systems, chemical feed is most critical in the Manganex Process. Continued excessive feed will produce a fully regenerated bed leading to leakage of potassium permanganate causing a pink tinge in the filter effluent. While not as dramatic as with the Manganex Process, over or under feeding will have effects on both aeration-filtration and chlorination-filtration. These effects can range from increased corrosiveness to bad taste. Conditions from improper feed need not be an operational concern if dealt with in system design.

In most cases, vertical turbine pumps are used for well water supplies. This type of pump is ideally suited to this purpose, providing efficient service. Multi-stage pumps, however, have high shut-off heads, often exceeding 250 psi. As most filter and piping systems are designed for pressures ranging from 75 to 125 psi, high pressure resulting



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from dead ending can cause serious damages to a direct pumping operation. Controls of filters, in such systems, whether manual or automatic, should be such as to prohibit dead endings. Continuous flow even during backwash and rinse cycles is often obtainable with standard valve arrangements

Backwashing is a basic requirement to all filtration systems. The supply of backwash water for pressure type systems normally comes from, either an elevated storage tanks(s), a hydro-pneumatic tank(s), a backwash storage tank, or filter effluent.³ Supply should be provided to allow for sequential backwash of filters while maintaining a predetermined minimum storage capacity. Storage facilities can be minimized by prohibiting backwash during low storage levels or by backwashing during periods of low demand. Another means for reducing or minimizing storage requirements is by using a bank of filters, thus allowing service filters, not employed in backwash, to furnish either backwash supply or storage water.

OTHER IRON AND MANGANESE REMOVAL SYSTEMS

Three iron and manganese removal systems have been described in this bulletin. Other processes, such as ion exchange, chlorine dioxide-filtration, and pH adjustment, have also been employed, with less frequency and success, to achieve the same ends. These systems are normally not competitive with other means of iron and manganese removal. Of these latter three systems chlorine dioxide-filtration has had the most success.

Chlorine dioxide is considered a strong oxidizing agent which will rapidly react with both iron and manganese. Chlorine dioxide is produced by reacting sodium chlorite with chlorine in an aqueous media. This method

has found limited application for manganese removal as the cost is generally prohibitive.

The flow diagram for chlorination-filtration (Fig. 2) is also typical for chlorine dioxide-filtration.

SUMMARY

Effective and reliable iron and manganese removal systems are available for treating a variety of ground water supplies. The selection of a process is based upon the evaluation of a number of factors summarized in Table 1.

Roberts Filter Manufacturing Company has broad experiences with these processes and has equipment and controls especially designed for their applications. Additional engineering data, drawings, and cost estimates are available from all Roberts' Representatives and Sales Offices.

1) Iron and manganese are considered ground water supply problems, although soluble iron and manganese may occur in surface waters. Treatment processes outlined in this bulletin are generally applicable to surface waters when used in conjunction with flocculation, sedimentation, and gravity filtration.

2) Sedimentation in varying degrees will occur in the retention tank depending upon detention time. In all cases provisions should be made for sludge removal.

3) Hydrogen sulfide removal of up to 5 mg can also be realized. However, above this level economics normally indicate aeration).

4) As much as 3 hours may be required for significant manganese precipitation.

5) Although the reaction time normally falls within the given range, certain soluble organic iron and manganese complexes require as much as ten minutes for conversion.

6) pH levels below 7.1 may cause deterioration of Manganese Greensand.

7) As with chlorination-filtration, hydrogen sulfide removal can be achieved with potassium permanganate. Normally 1 mg of H_2S requires 4 mg of $KMnO_4$ and, therefore, is uneconomical at higher H_2S concentrations.)

8) In certain isolated situations backwash with untreated raw water is permissible.



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**ENGINEERED
PRODUCT
INFORMATION**

KISCO WATER TREATMENT COMPANY

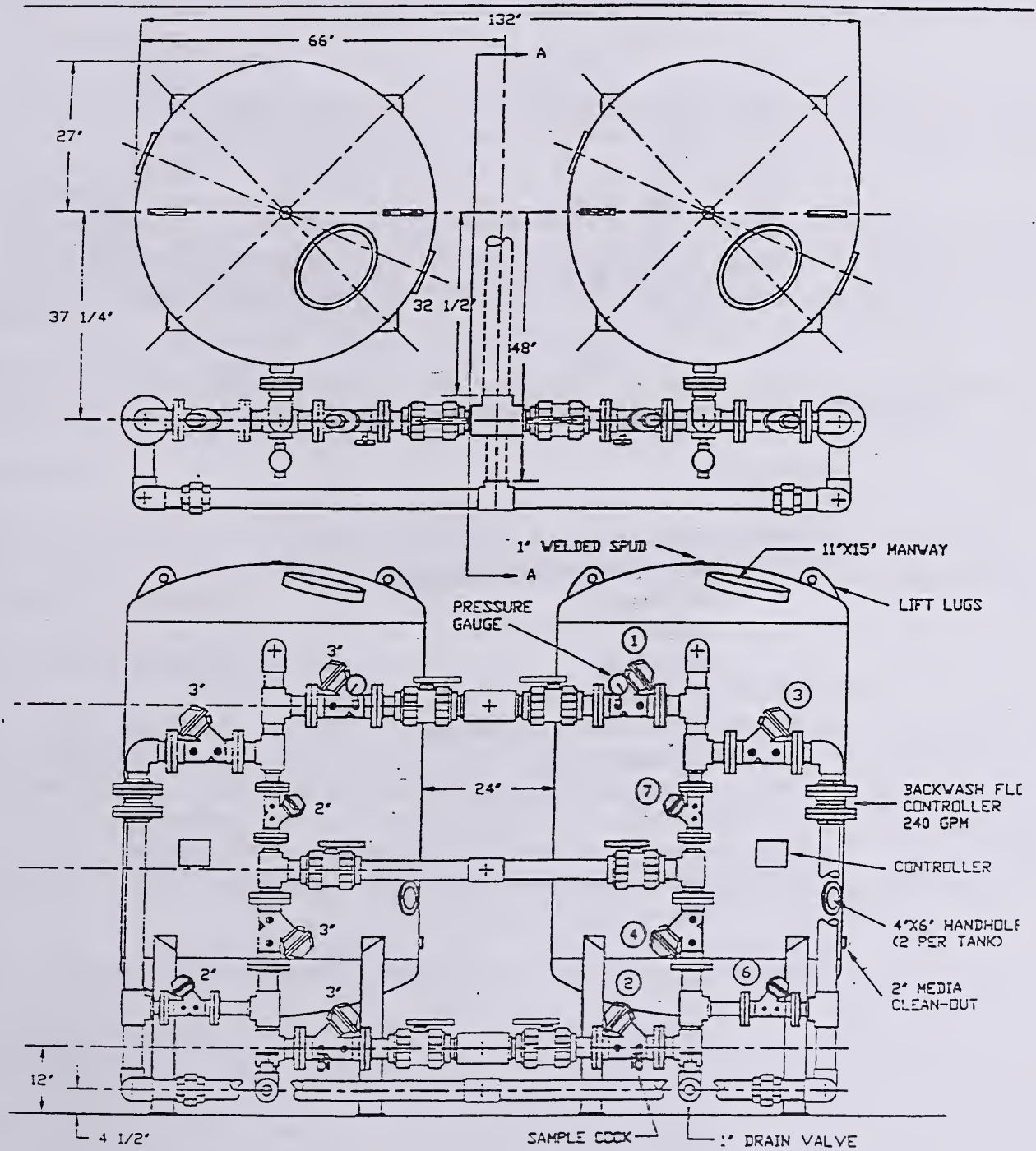
6950 Industrial Loop*Greendale, Wisconsin 53129*414-421-0444*Fax 414-421-1161

KISCO WATER TREATMENT COMPANY ENGINEERED PRODUCT INFORMATION

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SECTION FOUR	ION EXCHANGE DISSOLVED SOLIDS REMOVAL
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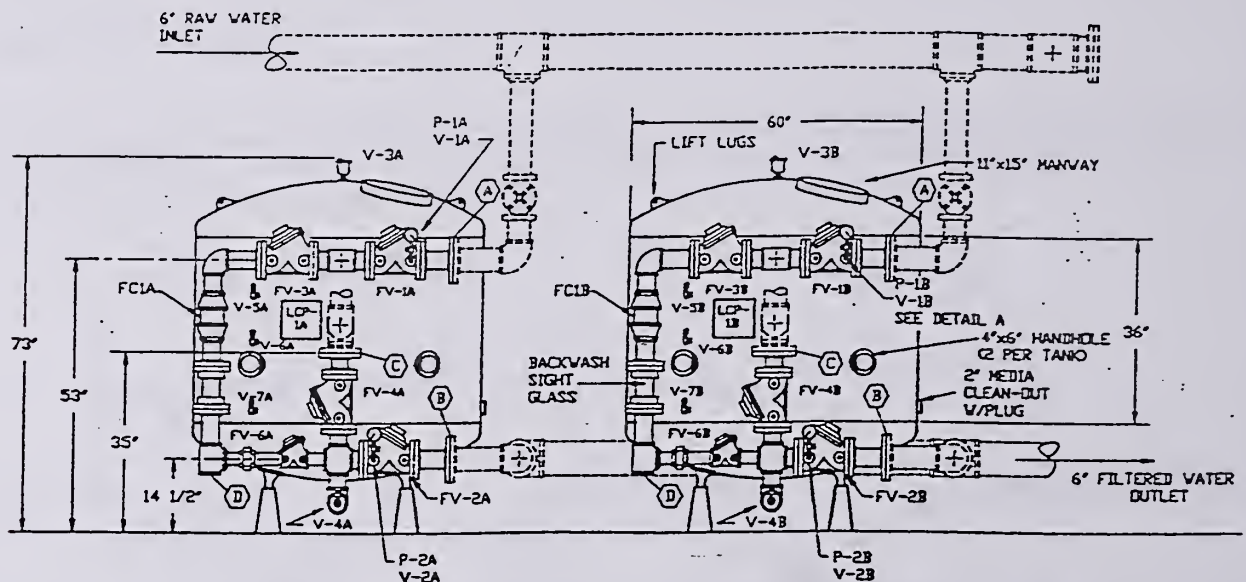


KISCO Water Treatment Company

6950 Industrial Loop *Greendale, Wisconsin 53129 *USA * 414-421-0444 *Fax 414-421-1161

SECTION TWO

MANGANESE GREENSAND FILTRATION



IRON REMOVAL VIA MANGANESE GREENSAND FILTRATION

- * Introduction
- * General
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 - Suggested Operating Conditions
 - Backwash
 - Capacity
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 - Physical Characteristics
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 - Regeneration
 - Permanganate Detector
- * Oxidation System Selection Chart
 - Curves
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MANGANESE GREENSAND FILTRATION

IRON REMOVAL VIA MANGANESE GREENSAND FILTRATION

Iron and manganese are two of the most undesirable constituents frequently found in water supplies. Iron removal can be accomplished by treating the ferrous iron with various types of oxidants by various methods.

Manganese greensand filter beds which are regenerated on a continuous feed basis with potassium permanganate (KMnO_4) have been proven to be among the most dependable and cost effective methods used to remove iron and manganese.

This system operates as a standard pressure filter system, with all containment and control advantages, and will remove trace amounts of iron up to about 5 mg/l. Water containing higher amounts of iron is usually retreated prior to the greensand to achieve almost total removal.

Final system design depends on the total content in the water of other reduced state elements. Kisco's design will include consideration of those conditions if known.

GENERAL

Manganese greensand, used for removing soluble iron and/or manganese as well as hydrogen sulfide from well water supplies, is a purple-black filter media processed from Glauconitic greensand.

CONTINUOUS REGENERATION

Continuous regeneration operation is recommended on well waters where iron removal is the main objective with or without the presence of manganese. It involves the feeding of a pre-determined amount of potassium permanganate (KMnO_4) usually in combination with chlorine (Cl_2) directly to the raw water prior to the unit containing manganese greensand. The chlorine should be fed upstream of the KMnO_4 with a contact time of 10-20 seconds if possible. Sufficient chlorine should be fed to produce the desired residual in the filter effluent.

The quantity of Cl_2 and KMnO_4 required can be estimated as follows:

$$\begin{aligned}\text{ppm } \text{Cl}_2 &= \text{ppm Fe} \\ \text{ppm } \text{KMnO}_4 &= 0.2 \times \text{ppm Fe} + 2 \times \text{ppm Mn}\end{aligned}$$

Without Cl_2 the KMnO_4 demand can be estimated as follows:

$$\text{ppm } \text{KMnO}_4 = 1 \times \text{ppm Fe} + 2 \times \text{ppm Mn}$$

MANGANESE GREENSAND FILTRATION

SUGGESTED OPERATING CONDITIONS

Backwash - The flow rate should be sufficient to produce approximately a 40% bed expansion.

Capacity - This is normally 500-700 grains/sq. ft. of bed area based on potassium permanganate demand. In addition to the manganese greensand an anthracite bed with a minimum depth of 15 inches is required. In any case the pressure drop should not exceed 10-12 psi.

Flow Rate - Normal flow rates with continuous regeneration are 2-5 gpm/sq. ft. High concentrations of iron and manganese usually require lower flow rates for equivalent run lengths. Rates in excess of 5 gpm/sq. ft. can be tolerated but a pilot unit should be operated to determine the effluent quality and run length.

The run length between backwashes can be estimated as follows:

Example: What is a run length on a water containing 1.7 ppm iron and 0.3 ppm manganese at a 4 gpm/sq. ft. operating rate?

$\text{KMnO}_4 \text{ demand} = (\text{Fe}) 1.7 \times 1 + (\text{Mn}) 0.3 \times 2 \text{ or } 2.3 \text{ ppm}$

$2.3 \text{ divided by } 17.1 = 0.13 \text{ grains/gal. (gpg)}$

$700 \text{ grains/sq. ft. divided by } 0.13 \text{ gpg} = 5200 \text{ gal/sq. ft.}$

$5200 \text{ gal/sq. ft. divided by } 4 \text{ gpm/sq. ft.} = 1300 \text{ min.} = 21.7 \text{ hours}$

Therefore the backwash frequency is approximately every 20-24 hours of operation.

INTERMITTENT REGENERATION

This method of operation is recommended on well waters where only manganese or manganese with small amounts of iron is to be removed. Treatment involves the regeneration of manganese greensand with a predetermined amount of KMnO_4 after a specified quantity of water has been processed. With this method the pressure drop is lower because the manganese is removed by contact oxidation on the manganese greensand. This eventually results in a larger manganese greensand grain size and bed growth, which can be removed either physically, by backwashing at a higher rate, or by sluicing from the bottom of the bed via suitable tank connection.

MANGANESE GREENSAND FILTRATION

SUGGESTED OPERATING CONDITIONS

Backwash Rate - This flow rate should be sufficient to produce approximately a 40% bed expansion.

Regeneration

KMnO ₄ Dosage	1.5 - 2.0 oz. KMnO ₄ /cu. ft.
KMnO ₄ Solution Strength	2-4 oz./gallon
KMnO ₄ Regeneration Rate	0.25 gpm/cu. ft.
KMnO ₄ Regeneration Time	30 minutes optimum
KMnO ₄ Regeneration Volume	7.5 gal/cu. ft.
Rinse Rate	1 gpm/cu. ft.
Rinse Volume	40 gal/cu. ft. or until all traces of KMnO ₄ are gone

NOTE: RECYCLE OF RINSE WATER WILL CONSERVE KMnO₄ AND RINSE WASTE WATER.

Capacity - 300 grains/cu. ft. Prechlorination is recommended especially if Mn is present.

Pressure Drop - Maximum pressure drop is 12 psi. If this pressure differential is reached before the capacity for Mn is obtained, manganese greensand can be backwashed without regenerating.

Flow Rate - 2-5 gpm/sq. ft. or 1-2 gpm/cu. ft. For higher flow rates contact supplier.

PHYSICAL CHARACTERISTICS

Physical Form	Black, nodular granules, shipped in a dry form
Shipping Weight	85 pounds per cubic foot net
Screen grading (dry)	18 to 60 mesh
Effective Size	0.30 to 0.35 mm
Uniformity Coefficient	1.40 to 1.55

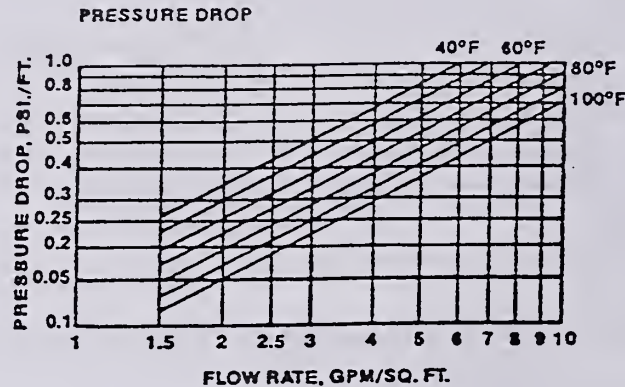
Suggested operating conditions:

pH Range	6.1 - 8.5 (See detailed information)
Maximum Temperature	Above 100°F contact supplier
Maximum Pressure Drop	12 psi
Backwash Rate	See detailed information
Service Flow Rate	See detailed information
Minimum Bed Depth	24" (18" in dual beds)

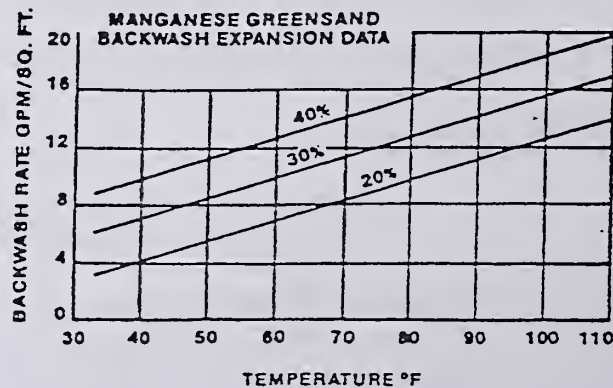
MANGANESE GREENSAND FILTRATION

HYDRAULIC CHARACTERISTICS

Pressure Drop - The approximate pressure drop for each foot of manganese greensand bed depth on a clean bed is shown in the graph. Pressure drop increases as run progresses. Do not exceed 12 psi.



Bed Expansion During Backwashing - After each service cycle the manganese greensand should be backwashed for 8-10 minutes to remove the suspended material collected during the run. The manganese greensand should be expanded a minimum of 35% during backwash. The bed expansion characteristics are shown in the graph.



Raw waters having a pH of 6.2 or higher can be passed through manganese greensand without pH correction; waters having a pH lower than 6.2 should be pH corrected to 6.2 - 6.5 before passing through the manganese greensand. If a pH higher than 6.5 is desired in the water system, the additional alkali should be added after the filters due to the adverse reaction (formation of a colloid) that sometimes occurs with the iron and alkali with pH over 6.5.

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MANGANESE GREENSAND FILTRATION

KMnO₄ Solution Strength - With continuous regeneration operation the KMnO₄ can be at any concentration up to 4 oz/gallon. See chart below for solubility of KMnO₄:

Solubility of KMnO₄ in Water

Temperature oF	Temperature oC	g./100 ml.	lb./gal.
32	0	2.78	0.23
68	20	6.51	0.54
104	40	12.53	1.05

Removing Fines - Although the manganese greensand is thoroughly washed before shipment, it is recommended that before it is put into service the material be thoroughly backwashed and the top layer of finer material be removed. This is especially important if anthracite is placed on top of the manganese greensand. Each bag contains sufficient material to compensate for removing about 1" of finer material.

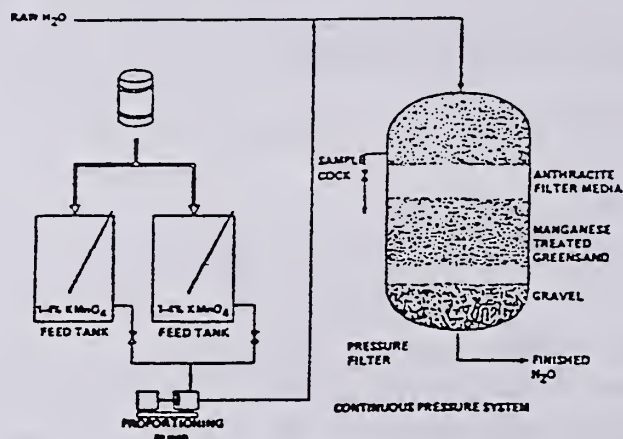
Regeneration - Although the manganese greensand is thoroughly regenerated before shipment, it is necessary prior to use to regenerate with potassium permanganate solution contacting the bed for approximately one hour. Usually 2 oz. of potassium permanganate per cubic foot is adequate. The filter must be rinsed of all traces of permanganate after regeneration.

Sometimes during the intermittent regeneration more or less than the equivalent amount of potassium permanganate is required. This is an oxidation-reduction reaction. If there are other reducing substances in the water more permanganate than the equivalent amount may be required. Conversely, where there are oxidizing substances in the water such as oxygen and/or chlorine under certain situations less potassium permanganate may be required. This can best be determined by close surveillance of operating data. Theoretically 300 grains of manganese is equivalent to 1.3 oz. of potassium permanganate per cubic foot.

Permanganate Detector - A properly operated manganese greensand filter should never have potassium permanganate or "pink water" in the treated water supply. If, however, it is felt that insurance against pink water should be provided use detectors to signal an alarm or shut down a system should pink water be detected in the treated water supply.

MANGANESE GREENSAND FILTRATION

Continuous KMnO₄ Feed in Manganese-Greensand System

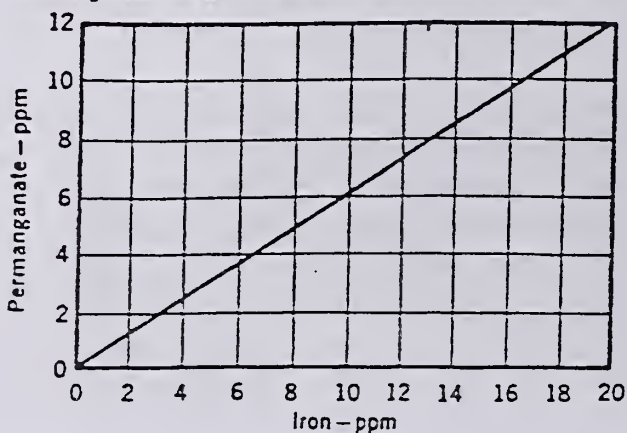


The following chart may be helpful in visualizing a workable flow diagram for handling iron, manganese and hydrogen sulfide removal. Selection is made on the basis of the total potassium permanganate demand, best determined at the jobsite, using a KMnO₄ demand test kit. The KMnO₄ demand also can be approximated from a water analysis by determining the sum of the following:

Iron (ppm as Fe) x 0.75	=	
Manganese (ppm as Mn) x 2.0	=	
Hydrogen Sulfide (ppm as H ₂ S)	=	
Organic Matter (ppm O.M.I.)	=	

Approximate KMnO₄ demand _____

Permanganate Demand Curve for Oxidation of Ferrous Iron.



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The potassium permanganate demand may also be calculated from the graphs shown above which illustrate the relationship between ferrous iron, manganous manganese, hydrogen sulfide and potassium permanganate demand.

Oxidation System Selection Chart

KMnO ₄ Demand	Type of Supply	Type of System
0.2 - 5.0 ppm	City water, piped-in supply, or partially treated supply.	Figure No. 10
0.2 - 5.0 ppm	Private well supply or municipality well.	Figure No. 11
5.1 - 15.0 ppm*	Private well supply.	Figure No. 12
5.1 - 15.0 ppm*	Municipal supply.	Figure No. 13
Over 15 ppm*	Private or Municipal supply.	Figure No. 14

* Economic considerations dictate application of aerators. Many waters having much lower than 15 ppm potassium permanganate demand, justify aeration to reduce costs. Since approximately 90% of the iron and 15% of the manganese can be removed by aeration, thus reducing the permanganate demand, calculation can be made to determine the estimated saving. The savings in many cases will more than pay for an aerator, especially where large quantities of water are to be treated.

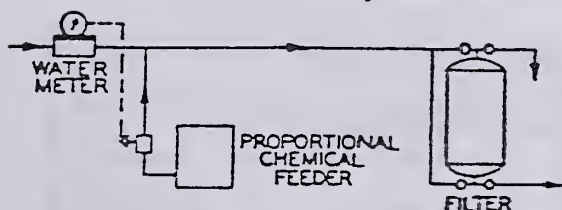


Fig. 10. System using meter-paced proportional chemical feeder.

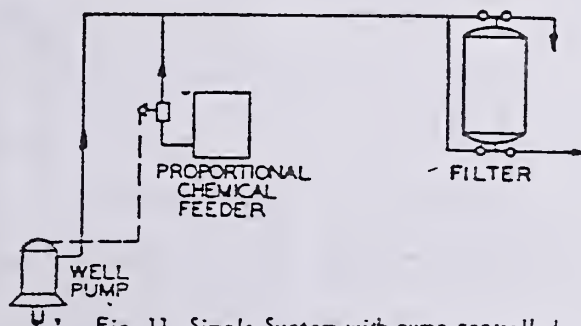


Fig. 11 Simple System with pump controlled simultaneously with well pump operation.

MANGANESE GREENSAND FILTRATION

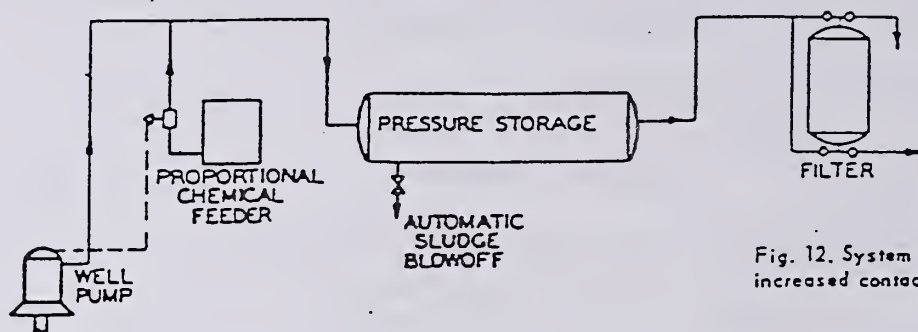


Fig. 12. System with pressure tank for increased contact time and/or sludge removal.

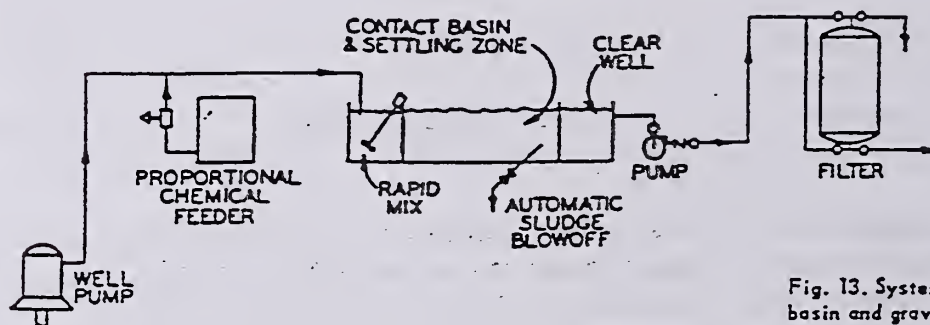
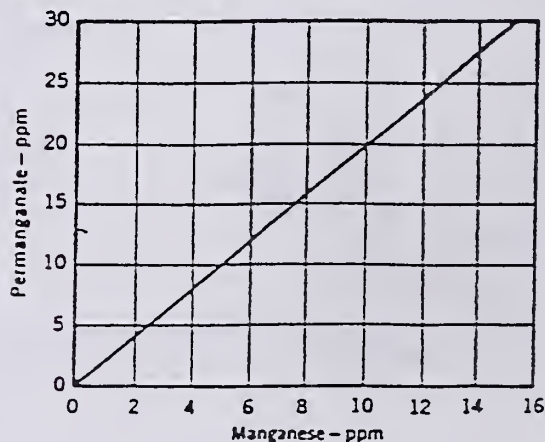
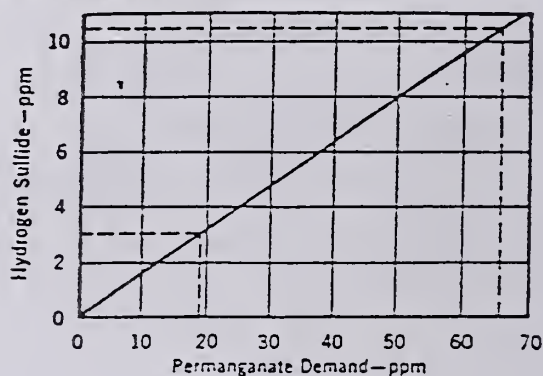


Fig. 13. System employing contact basin and gravity settling zone.

Permanganate Demand Curve for Oxidation of Manganous Manganese.



Permanganate Demand Curve for Conversion of Hydrogen Sulphide.



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